## LCA Case Studies

# Life Cycle Inventory Information of the United States Electricity System

**Seungdo Kim[1] and Bruce E. Dale[2]**

[1] Department of Chemical Engineering & Materials Science, Room 2527 Engineering Building, Michigan State University, East Lansing, MI 48824-1226, USA (kimseun@msu.edu)
[2] Department of Chemical Engineering & Materials Science, Room 2527 Engineering Building, Michigan State University, East Lansing, MI 48824-1226, USA (bdale@egr.msu.edu)

**DOI: http://dx.doi.org/10.1065/lca2004.09.176**

**Abstract**

**Goal and Scope.** This study estimates the life cycle inventory (LCI) of the electricity system in the United States, including the 10 NERC (North American Electric Reliability Council) regions, Alaska, Hawaii, off-grid non-utility plants and the US average figures. The greenhouse gas emissions associated with the United States electricity system are also estimated.

**Methods.** The fuel mix of the electricity system based on year 2000 data is used. The environmental burdens associated with raw material extraction, petroleum oil production and transportation for petroleum oil and natural gas to power plants are adopted from the DEAM™ LCA database. Coal transportation from a mining site to a power plant is specified with the data from the Energy Information Administration (EIA), which includes the mode of transportation as well as the distance traveled. The gate-to-gate environmental burdens associated with generating electricity from a fossil-fired power plant are obtained from the DEAM™ LCA database and the eGRID model developed by the United States Environmental Protection Agency. For nuclear power plants and hydroelectric power plants, the data from the DEAM™ LCA database are used.

**Results and Discussion.** Selected environmental profiles of the US electricity system are presented in the paper version, while the on-line version presents the whole LCI data. The overall US electricity system in the year 2000 released about 2,654 Tg $CO_2$ eq. of greenhouse gas emissions based on 100-year global warming potentials with 193 g $CO_2$ eq. $MJe^{-1}$ as an weighted average emission rate per one MJ electricity generated. Most greenhouse gases are released during combusting fossil fuels, accounting for 78–95% of the total. The greenhouse gas emissions released from coal-fired power plants account for 81% of the total greenhouse gas emissions associated with electricity generation, and natural gas-fired power plants contribute about 16% of the total. The most significant regions for the total greenhouse gas emissions are the SERC (Southeastern Electric Reliability Council) and ECAR (East Central Area Reliability Coordination Agreement) regions, which account for 22% and 21% of the total, respectively. A sensitivity analysis on the generation and consumption based calculations indicates that the environmental profiles of electricity based on consumption are more uncertain than those based on generation unless exchange data from the same year are available because the exchange rates (region to region import and export of electricity) vary significantly from year to year.

**Conclusions and Outlook.** Those who are interested in the LCI data of the US electricity system can refer to the on-line version. When the inventory data presented in the on-line version are used in a life cycle assessment study, the distribution and transmission losses should be taken into account, which is about 9.5% of the net generation [1]. The comprehensive technical information presented in this study can be used in estimating the environmental burdens when new information on the regional fuel mix or the upstream processes is available. The exchange rates presented in this study also offer useful information in consequential LCI studies.

**Keywords:** Electricity system, US; generation efficiency; greenhouse gas emissions; life cycle inventory; NERC regions (North American Electric Reliability Council); United States electricity system

## Introduction

Most industrial processes directly (or indirectly) link to the electricity system. Thus life cycle inventory (LCI) information on the electricity system is an important factor in a life cycle assessment (LCA) study. LCI data for the United States electricity system are available in commercial LCA databases, but these are based on information from the mid-1990s. Thus, updated and complete LCI information on the US electricity system would benefit many LCA studies.

The annual net electricity generation in the United States was around 3.86 EWh (exa-Wh = $10^{15}$ kWh) in 2002, while 3.83 EWh in 2000 [1]. Fossil fuels (i.e., coal, petroleum, natural gas) are the primary energy sources for electricity generation, accounting for about 70% of the net generation. Nuclear power plants generate about 20% of the total electricity, hydroelectric power plants contribute about 7% of the total, and other energy sources (e.g., renewable energy, waste material, etc.) generate about 3%.

The United States Environmental Protection Agency (USEPA) developed the eGRID model, which includes comprehensive information on the US electricity system in 2000 [2]. The eGRID model utilizes the ten regions from the NERC and adds three more regions, including Alaska, Hawaii, and off-grid non-utility plants. State-based and generation plant-based information are also available in the eGRID model. Information on the annual heat input and the net electricity generation of each power plant is presented in the eGRID model. The eGRID model also provides the limited gate-to-gate air emissions for $CO_2$, $NO_x$, $SO_2$ and Hg. The information provided by the eGRID model is very useful and comprehensive, but there are limitations on directly using it in an LCA study because the data for upstream processes (e.g., extraction, fuel production, transportation of fuel) are not provided, and only limited air emissions are presented.

To establish accurate LCI information on the US electricity system, information on the upstream processes (e.g., fuel extraction, fuel production, etc.) and other emissions not addressed in the eGRID model should be included. In this study, we estimate LCI information for the US electricity system based on the eGRID model and the DEAM™ LCA database [3] by including the upstream processes and other emissions.

## 1 Goal of Study

The goals of this study are: 1) to establish LCI information on the US electricity system based on the regions presented in **Fig. 1**, off-grid non-utility power plants and the US average, and 2) to estimate greenhouse gas emissions associated with the US electricity system.

## 2 Method and Background Data

One MJe of electricity generated in the United States (i.e., generation-based) is defined as a functional unit in estimating LCI of the US electricity system. Five types of energy sources (i.e., coal, petroleum oil, natural gas, nuclear and hydropower) are considered, and other energy sources (i.e., wind, solar energy, waste material, geothermal energy) are not taken into account due to their small contribution to the fuel mix.

The LCI information presented in this study is based on the fuel mix in the year 2000, which is summarized in **Table 1**. Coal was the primary energy source for electricity generation in the United States in 2000, accounting for about 52% of the total net generation. Coal-fired power plants in the ECAR, SERC and WSCC regions generate about 1.2 EWh,

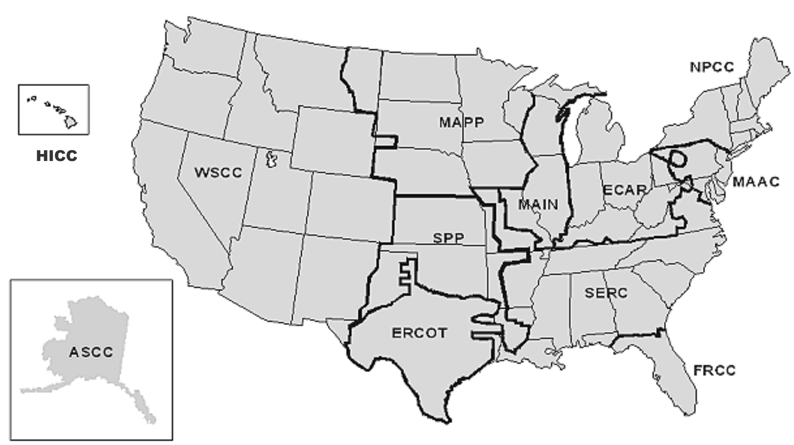


**Fig. 1:** North American Electric Reliability Council regions for the United States, Alaska and Hawaii [ASCC: Alaska Systems Coordinating Council, ECAR: East Central Area Reliability Coordination Agreement, ERCOT: Electric Reliability Council of Texas, FRCC: Florida Reliability Coordinating Council, HICC: Hawaiian Islands Coordinating Council, MAAC: Mid-Atlantic Area Council, MAIN: Mid-America Interconnected Network, MAPP: Mid-Continent Area Power Pool, NPCC: Northwest Power Coordinating Council, SERC: Southeastern Electric Reliability Council, SPP: Southwest Power Pool, WSCC: Western Systems Coordinating Council] [1]

**Table 1:** Fuel mix and fraction of electricity generation in the United States in 2000 based on generation (3.83 EWh) [Unit: %] [2]

| | Coal** | Natural gas | Petroleum oil | Nuclear | Hydro-electric | Others* | Fraction of the total US electricity generation |
|---|---|---|---|---|---|---|---|
| ASCC | 9.24 | 62.60 | 10.98 | – | 17.18 | – | 0.15 |
| ECAR | 87.23 | 2.73 | 0.51 | 8.08 | 0.44 | 1.02 | 15.45 |
| ERCOT | 34.89 | 50.53 | 0.86 | 11.97 | 0.17 | 1.57 | 8.20 |
| FRCC | 35.68 | 22.91 | 18.51 | 17.53 | 0.00 | 5.36 | 4.81 |
| HICC | 14.38 | – | 73.79 | – | 0.94 | 10.89 | 0.29 |
| MAAC | 44.49 | 8.65 | 2.81 | 39.49 | 1.21 | 3.35 | 7.01 |
| MAIN | 55.69 | 2.59 | 0.36 | 39.21 | 0.97 | 1.17 | 7.70 |
| MAPP | 75.88 | 1.11 | 0.48 | 12.02 | 8.58 | 1.94 | 4.70 |
| NPCC | 17.07 | 24.71 | 12.80 | 25.28 | 12.84 | 7.31 | 6.82 |
| OFF-G+ | – | 100.00 | – | – | – | – | 0.01 |
| SERC | 54.64 | 10.20 | 1.41 | 28.55 | 2.37 | 2.83 | 22.53 |
| SPP | 68.24 | 22.90 | 0.43 | 4.85 | 2.20 | 1.37 | 4.89 |
| WSCC | 32.11 | 23.31 | 0.59 | 11.10 | 28.20 | 4.68 | 17.45 |
| US overall | 51.49 | 15.80 | 2.83 | 19.76 | 7.11 | 3.01 | 100 |

** Coal includes bituminous coal, sub-bituminous coal and lignite
* Others include renewable, wind, solar and other fossil energy
+ Off-grid non-utility power plants

Table 2: Mining practices for coal used in coal-fired power plant [4]

| | Bituminous coal | | Sub-bituminous coal | | Lignite | |
|---|---|---|---|---|---|---|
| | Surface mining | Underground mining | Surface mining | Underground mining | Surface mining | Underground mining |
| ASCC | – | – | 100.0 | – | – | – |
| ECAR | 56.3 | 43.7 | 99.9 | 0.1 | – | – |
| ERCOT | 100.0 | | 100.0 | – | 100.0 | – |
| FRCC | 24.7 | 75.3 | – | – | – | – |
| HICC | – | – | 99.2 | 0.8 | – | – |
| MAAC | 32.4 | 67.6 | – | – | – | – |
| MAIN | 14.8 | 85.2 | 100.0 | – | – | – |
| MAPP | 22.8 | 77.2 | 100.0 | – | 100.0 | – |
| NPCC | 20.8 | 79.2 | – | – | – | – |
| SERC | 36.8 | 63.2 | 94.5 | 5.5 | – | – |
| SPP | 69.4 | 30.6 | 100.0 | – | 100.0 | – |
| WSCC | 42.7 | 57.3 | 100.0 | – | – | – |
| US weighted average | 43.1 | 56.9 | 99.2 | 0.8 | 100.0 | – |

contributing about 61% of the total net generation from coal-fired power plants in the United States. The next most important energy sources for electricity in the United States are nuclear energy and natural gas.

The environmental burdens associated with raw material extraction and petroleum oil production are adopted from the DEAM™ LCA database. The mining practices (i.e., surface and underground) for coal used in coal-fired power plants are specified, which are available in the Energy Information Administration's (EIA) report [4]. **Table 2** summarizes the mining practices for coal. As seen in Table 2, the mining practices for coal vary from region to region and also with the types of coal. Most sub-bituminous and lignite are extracted by surface mining. Underground mining practices account for 57% of the total amount of bituminous coal extracted as an US weighted average.

Information on coal transportation from a mining site to a power plant is available in a database published by the EIA [5], which includes the mode of transportation as well as the distance traveled. However, the coal transportation information for the ASCC and HICC regions is not available through the EIA at this time. We estimate the coal transportation data for these regions with the traveling distance for commodities for both regions [6–7] and the US average transportation mode for coal. However, the railroad transportation in the HICC region is excluded because railroad transportation for commodities is very small in Hawaii [7]. The transportation of coal used in coal-fired power plants is summarized in **Table 3**. It is assumed that the transportation mode and traveling distance are independent of the coal type. The primary transportation mode for coal in the United States is by railroad and accounts for 70% of the total quantity of coal used in power generation. It is assumed that the energy

Table 3: Transportation of coal used in coal-fired power plants from 1992 to 1999 [5–7]

| | Transportation mode [mass-basis%] | | | | Distance [km] | | | |
|---|---|---|---|---|---|---|---|---|
| | Barge | Rail | Truck | Conveyor and pipe | Barge | Rail | Truck | Conveyor and pipe |
| ASCC | 12.16[A] | 69.65[A] | 9.20[A] | 8.99[A] | 1300.35[B] | 685.58[B] | 85.30[B] | n.a. |
| ECAR | 36.35 | 47.18 | 8.55 | 7.92 | 364.22 | 813.69 | 54.59 | n.a. |
| ERCOT | – | 99.92 | 0.08 | – | – | 2388.58 | 136.83 | – |
| FRCC | 43.04 | 51.96 | 5.00 | – | 3287.30 | 1241.57 | 18.59 | – |
| HICC * | 40.08[B] | – | 30.30[B] | 29.62[B] | 384.63[B] | – | 16.09[B] | n.a. |
| MAAC | 17.69 | 82.31 | – | – | 260.37 | 678.28 | – | – |
| MAIN | 9.71 | 87.58 | 2.39 | 0.31 | 183.75 | 1297.90 | 91.31 | n.a. |
| MAPP | – | 88.11 | 0.56 | 11.34 | – | 1149.19 | 48.28 | n.a. |
| NPCC | 36.13 | 63.85 | 0.02 | – | 1018.48 | 707.41 | 96.56 | – |
| SERC | 9.15 | 81.10 | 7.67 | 2.07 | 722.55 | 918.59 | 11.84 | 1.03 |
| SPP | 1.03 | 90.22 | 4.15 | 4.60 | 675.78 | 1559.34 | 30.77 | n.a. |
| WSCC | – | 42.88 | 22.84 | 34.28 | – | 502.09 | 36.33 | 443.44 |
| US weighted average | 12.16 | 69.65 | 9.20 | 8.99 | 675.78 | 1124.96 | 45.69 | 90.80 |

A: US weighted average
B: Data from the US Census 1997 [6–7]
n.a.: Not available
* Coal used in Hawaii is imported from Australia [8]

source for conveyor and pipe transportation is electricity generated in a coal-fired power plant. In the HICC region, overseas transportation from Australia to Hawaii [8] is included in the LCI analysis. Data for the transportation of other fossil fuels in the DEAM™ LCA database, which presents aggregated information, are used.

Efficiency of electricity generation in a fossil fuel-fired power plant allows us to estimate the quantity of fuel used, calculating based on Eq. (1).

$$Q_{i,j} = \frac{1}{eff_j} \cdot \frac{1}{HHV_i} \tag{1}$$

where

$Q_{i,j}$: Quantity of the $i^{th}$ fuel used for generating 1MJ of electricity in the $j^{th}$ type of power plant [kg MJe$^{-1}$]
$eff_j$: Efficiency of the $j^{th}$ type of power plant in a region [= $EL_j/AH_j$] []
$AH_j$: Annual heat input in the $j^{th}$ type of power plant in a region [MJ]
$EL_j$: Annual net generation in the $j^{th}$ type of power plant in a region [MJe]
$HHV_i$: Higher heating value of the $i^{th}$ fuel [MJ kg$^{-1}$]

**Subscripts:**
i: Type of fossil fuel (i.e., coal, petroleum oil, natural gas)
j: Type of power plant (i.e., bituminous coal-fired plant, sub-bituminous coal-fired plant, lignite-fired plant, petroleum oil-fired plant, and natural gas-fired plant)

For a combined heat and power plant (CHP) in which electricity and useful thermal energy (i.e., heat and steam) are produced, allocation between electricity and thermal output is required to estimate the efficiency of electricity generation. The eGRID model has allocated the environmental burdens to electricity by an electric allocation factor. The eGRID model [2] addressed: "An allocation factor that discounts useful thermal output by 50 percent has been used previously by the Federal Energy Regulatory Commission … This allocation is consistent with current technology whereby steam is converted to electricity at approximately 50 percent efficiency."

The quality of fossil fuel used in the electricity generation (e.g., heating value, sulfur content, ash content, etc.) is available in a report by the EIA [4]. The regional efficiency of each fossil fuel-fired power plant and the heating value of each fossil fuel are summarized in **Table 4**, in which the efficiency is calculated by Eq. (1). The efficiency in a coal-fired power plant depends on the types of coal consumed. However, the eGRID model does not specify the types of coal used in a specific coal-fired power plant. These coal-fired power plants are sorted into the type of coal used according to the information in a report by EIA [4] in order to estimate the efficiency of each type of coal-fired power plant. The term 'Not applicable' in Table 4 means that that fuel is not used in generating electricity in a particular region. When the required information is not available, the US weighted average values are applied. For example, the US weighted average efficiency of sub-bituminous coal-fired power plants is used as the efficiency of sub-bituminous coal-fired power plant in the HICC region due to the lack of data for that region. This practice is applied throughout this study when the data are unavailable. Anthracite is not taken into account in this study because the quantity used in the electricity system is very small [9]. Weighted average electricity efficiency is 32% for bituminous coal, 30% for sub-bituminous coal, 29% for lignite, 37% for natural gas, and 33% for petroleum oil. Table 4 shows that the heating value of each fuel varies with the region, but the differences are not significant. The quantity of fuel used in the power plants within a region can be calculated with the values presented in Table 4.

The gate-to-gate environmental burdens associated with generating electricity from a fossil-fired power plant are obtained from the DEAM™ LCA database and the eGRID model. The DEAM™ LCA database estimates the emissions associated with generating electricity from each type of fossil fuels, based on reports by the United States Environmental Protection Agency [10]. For nuclear power plants and hydroelectric power plants, data from the DEAM™ LCA database are used because current information on these two classes of power plants is not available in either the EIA reports or the eGRID model.

**Table 4:** Efficiency of electricity generation and heating value of each fossil fuel-fired power plant in 2000

| | Efficiency [%] | | | | | Higher heating value [MJ kg$^{-1}$] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bituminous coal | Sub-bituminous coal | Lignite | Natural gas | Petroleum oil | Bituminous coal | Sub-bituminous coal | Lignite | Natural gas | Petroleum oil |
| ASCC | N/A | 25.43 | N/A | 31.66 | 35.31 | N/A | 17.93 | N/A | 56.49 | 49.80 |
| ECAR | 31.43 | 30.59 [A] | N/A | 40.99 | 33.87 | 28.32 | 20.92 | N/A | 56.16 | 45.74 |
| ERCOT | 32.90 [A] | 33.6 | 29.12 [A] | 40.71 | 32.21 | 28.37 [A] | 19.82 | 14.69 | 56.48 | 45.93 |
| FRCC | 31.71 | N/A | N/A | 39.30 | 32.21 | 29.63 | N/A | N/A | 57.39 | 45.69 |
| HICC | N/A | 30.59 [A] | N/A | N/A | 33.34 | N/A | 20.56 [A] | N/A | N/A | 49.80 |
| MAAC | 34.77 | N/A | N/A | 40.39 | 32.90 | 30.15 | N/A | N/A | 57.62 | 45.78 |
| MAIN | 30.39 | 31.01 | v | 43.13 | 33.79 | 26.88 | 20.83 | N/A | 55.79 | 45.64 |
| MAPP | 30.67 | 30.75 | 29.07 | 34.28 | 30.41 | 27.48 | 20.14 | 15.51 | 56.34 | 45.50 |
| NPCC | 33.67 | N/A | N/A | 39.67 | 32.74 | 30.31 | N/A | N/A | 56.71 | 49.91 |
| OFF-G | N/A | N/A | N/A | 24.52 | N/A | N/A | N/A | N/A | 56.49 | N/A |
| SERC | 31.49 | 30.59 [A] | N/A | 42.58 | 32.21 | 28.86 | 20.45 | N/A | 56.89 | 45.78 |
| SPP | 32.90 | 30.59 [A] | 29.12 [A] | 33.31 | 31.82 | 26.84 | 20.40 | 15.61 | 56.36 | 46.32 |
| WSCC | 29.49 | 31.02 | N/A | 36.04 | 31.85 | 26.03 | 21.05 | N/A | 56.00 | 45.57 |
| US weighted average | 32.90 | 30.59 | 29.12 | 38.29 | 32.21 | 28.37 | 20.56 | 15.19 | 56.49 | 49.80 |

A: US weighted average
N/A: Not applicable

The inventory information on nuclear power plant includes $UF_6$ manufacturing, accumulation and fuel rod manufacturing [3]. However, there is no information on transportation from fuel rod manufacturing to a power plant, which is treated as a data gap. In hydroelectric power plants, only greenhouse gas emissions due to the influence of the reservoir carbon cycle from new biomass are taken into account [3].

$CO_2$, $NO_x$, $SO_x$ and Hg emissions from fossil-fired power plants presented in the eGrid model are used instead of values given by the DEAM™ LCA database. The four air emissions associated with natural gas-fired and petroleum oil-fired power plants presented in the eGRID model can be extracted with respect to the individual fuel. However, the air emissions of coal-fired power plants in the eGRID model are not specified by coal type. Similar procedures in the efficiency calculation are followed to categorize emissions with respect to the type of coal. When the information on coal type in a region is not available, carbon dioxide emission factors for each coal-fired power plant are estimated by a linear regression on carbon dioxide emission factors versus the quantity of coal used in coal-fired power plants. The linear regression results are presented in **Appendix A, p. 304.1** (online only at <http://dx.doi.org/10.1065/lca2004.09.176>). For example, carbon dioxide emissions in bituminous coal-fired power plants in the ERCOT region are estimated through quantity of bituminous coal (=0.107 kg $MJe^{-1}$) and $CO_2$ emission rate (=2,510.9 g $kg^{-1}$ of coal) because the required data are not available. Results of the four air emissions in each power plant are summarized in **Table 5**.

Carbon dioxide emissions range from 247 to 303 g $MJe^{-1}$ in a bituminous coal-fired power plant, 248 to 360 g $MJe^{-1}$ in a sub-bituminous coal-fired power plant, 313 to 338 g $MJe^{-1}$ in a lignite-fired power plant, 161 to 373 g $MJe^{-1}$ in a petroleum oil-fired power plant, and 138 to 215 g $MJe^{-1}$ in a natural gas-fired power plant. Although the carbon content in lignite is lower than other types of coal, a lignite-fired power plant releases more carbon dioxide per MJe because its efficiency of electricity generation and heating value are lower than those of other types of coal. A natural gas-fired power plant provides less carbon dioxide emissions than other fossil fuel-fired power plants. The following section represents the inventory data of the US electricity systems, which are estimated from emissions from the DEAM™ LCA database and the eGRID mode.

**Table 5:** Selected emissions in fossil-fired power plants [Unit: g $MJe^{-1}$]

| | Bituminous coal | | | | Sub-bituminous coal | | | | Lignite | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | NOx | $SO_2$ | Hg | $CO_2$ | NOx | $SO_2$ | Hg | $CO_2$ | NOx | $SO_2$ | Hg |
| ASCC | – | – | – | – | 360.02 | 1.36E+00 | 7.59E-01 | 2.99E-06 | – | – | – | – |
| ECAR | 267.94 | 6.82E-01 | 1.92E+00 | 6.74E-06 | 285.12 | 7.76E-01 | 8.46E-01 | 5.28E-06 | – | – | – | – |
| ERCOT | 269.04[A] | 6.50E-01[B] | 1.77E+00[B] | 8.95E-06[B] | 262.47 | 3.67E-01 | 8.95E-01 | 1.04E-05 | 317.96 | 4.44E-01 | 8.05E-01 | 3.80E-06 |
| FRCC | 247.46 | 5.92E-01 | 9.47E-01 | 2.60E-06 | – | – | – | – | – | – | – | – |
| HICC | – | – | – | – | 247.77 | 5.52E-01 | 2.81E-01 | 1.36E-06 | – | – | – | – |
| MAAC | 261.29 | 6.06E-01 | 1.97E+00 | 9.60E-06 | – | – | – | – | – | – | – | – |
| MAIN | 302.85 | 5.61E-01 | 1.36E+00 | 7.56E-06 | 290.13 | 7.16E-01 | 1.20E+00 | 1.11E-05 | – | – | – | – |
| MAPP | 288.10 | 4.92E-01 | 9.14E-01 | 9.08E-06 | 284.45 | 5.92E-01 | 6.51E-01 | 6.08E-06 | 337.90 | 8.19E-01 | 1.22E+00 | 7.78E-06 |
| NPCC | 264.34 | 4.90E-01 | 1.91E+00 | 4.08E-06 | – | – | – | – | – | – | – | – |
| OFF-G | – | – | – | – | – | – | – | – | – | – | – | – |
| SERC | 276.69 | 8.90E-01 | 1.11E+00 | 1.94E-06 | 306.15 | 4.66E-01 | 1.09E+00 | 1.24E-05 | – | – | – | – |
| SPP | 284.37[A] | 6.5E-01[B] | 1.77E+00[B] | 8.95E-06[B] | 292.37[A] | 6.97E-01[B] | 8.83E-01[B] | 3.58E-06[B] | 312.55[A] | 7.64E-01[B] | 1.17E+00[B] | 7.22E-06[B] |
| WSCC | 278.52 | 7.11E-01 | 5.35E-01 | 3.88E-06 | 301.92 | 1.15E+00 | 1.03E+00 | 6.43E-06 | – | – | – | – |
| US weighted average | 269.04 | 6.50E-01 | 1.77E+00 | 8.95E-06 | 290.03 | 6.97E-01 | 8.83E-01 | 3.58E-06 | 321.20 | 7.64E-01 | 1.17E+00 | 7.22E-06 |

| | Petroleum oil | | | Natural gas | | |
|---|---|---|---|---|---|---|
| | $CO_2$ | NOx | $SO_2$ | $CO_2$ | NOx | $SO_2$ |
| ASCC | 233.81 | 2.19E+00 | 9.73E-01 | 160.83 | 4.22E-01 | 5.04E-03 |
| ECAR | 249.45 | 1.17E+00 | 5.10E-01 | 137.77 | 1.81E-01 | 2.96E-02 |
| ERCOT | 372.8 | 8.34E-01 | 1.49E+00 | 140.17 | 2.48E-01 | 7.43E-03 |
| FRCC | 161.19 | 4.02E-01 | 8.68E-01 | 138.88 | 2.04E-01 | 2.44E-01 |
| HICC | 234.54 | 7.42E-01 | 6.89E-01 | – | – | – |
| MAAC | 256.05 | 6.07E-01 | 1.91E+00 | 119.11 | 1.04E-01 | 1.55E-02 |
| MAIN | 241.34 | 1.31E+00 | 2.62E-01 | 180.87 | 1.97E-01 | 5.68E-02 |
| MAPP | 315.58 | 1.11E+00 | 1.03E+00 | 172.59 | 3.92E-01 | 2.90E-02 |
| NPCC | 243.69 | 3.43E-01 | 1.12E+00 | 146.93 | 1.22E-01 | 3.70E-02 |
| OFF-G | – | – | – | 215.04 | 3.31E-01 | 6.05E-03 |
| SERC | 245.61 | 7.87E-01 | 2.17E+00 | 166 | 3.07E-01 | 5.76E-02 |
| SPP | 292.27 | 2.10E+00 | 1.60E-01 | 200.24 | 3.84E-01 | 2.85E-02 |
| WSCC | 292.35 | 8.18E-01 | 8.71E-01 | 144.18 | 1.47E-01 | 4.28E-03 |
| US weighted average | 203.99 | 4.69E-01 | 1.04E+00 | 149.51 | 2.16E-01 | 3.18E-02 |

A: Estimated by a linear regression (see Appendix A, online only at <http://dx.doi.org/10.1065/lca2004.09.176>). Carbon dioxide emissions versus quantity of coal used in coal-fired power plant)
B: US weighted average

## 3 Results and Discussion

### 3.1 Inventory analysis

Fossil fuels used in the overall US electricity system are about 68.9 g $MJe^{-1}$ for coal, 2.6 g $MJe^{-1}$ for crude oil, and 8.9 g $MJe^{-1}$ for natural gas. The highest coal consumption regions are ECAR, MAPP and SPP in which over 100 g of coal is consumed in generating 1 MJe of electricity. The fuel mix of coal-fired power plants in these three regions is more than 60%. Non-renewable energy consumption (including fossil energy and nuclear energy) in the overall US electricity system is 2.9 MJ $MJe^{-1}$. The highest non-renewable energy consumption per 1 MJe of electricity occurs in the off-grid non-utility plants (OFF-G) due to lower generation efficiency (24.5%) compared to other regions. This is illustrated in **Table 6**, in which the distribution and transmission losses are not taken into account. Non-renewable energy use in coal-fired power plants contributes about 59% of the total non-renewable energy used in the overall US electricity system, and nuclear power plants contribute 21% of the total.

Selected environmental burdens associated with generating electricity in the United States are summarized in Table 7. Values in Table 7 include the emissions released from raw material extraction, fuel production and transportation, and within the power plant. $CH_4$, $N_2O$ and particulates are obtained from the DEAM™ LCA database. Due to space limitation in the paper version of this paper, only selected environmental burdens are presented here. However, those who are interested in the whole set of inventory data associated with the US electricity system can refer to our on-line version. Carbon dioxide emissions from the US electricity system range from 134 to 291 g $MJe^{-1}$ with 202 g $MJe^{-1}$ as a weighted average value. Coal-fired power plants in most regions, except for ASCC, HICC and OFF-G, are the primary source of carbon dioxide emissions. In the ASCC region, natural gas-fired power plants are the major source of carbon dioxide emissions, accounting for 68% of the total $CO_2$ emissions in this region. Petroleum oil-fired power plants (83% of the total) are the major source of carbon dioxide emissions released in the HICC region. More than 80% of carbon dioxide emissions in the US electricity system are released from coal-fired power plants followed by natural gas-fired power plants, which account for 15% of the total.

The US electricity system releases $NO_x$ at the rate of about 0.47 g $MJe^{-1}$, and about 83% of total $NO_x$ emissions are associated with coal-fired power plants. The highest $NO_x$ emission rate associated with generating electricity occurs in the ASCC region due to $NO_x$ emissions from natural gas-fired power plants, while the lowest $NO_x$ emissions occur in the NPCC region. Nitrous oxide ($N_2O$) emissions are relatively higher in the ERCOT, MAPP and SPP regions than in other regions because these three regions use lignite in coal-fired power plants. Burning lignite produces relatively higher $N_2O$ emissions compared to burning other fossil fuels [10]. $SO_x$ emissions from the US electricity system range from 0.01 to 1.55 g $MJe^{-1}$ with 0.75 g $MJe^{-1}$ as a weighted average value. The electricity system in the ECAR region releases the highest $SO_x$ emissions because of the high percentage of fuel mix of coal-fired power plants. The primary source of the emissions listed in **Table 7** in the US electricity system is also coal-fired power plants due to its dominant position in the fuel mix.

The combustion of fossil fuels in the US electricity system releases more air emissions (except for $CH_4$ and particulates) as summarized in Table 7 than the upstream processes (e.g., raw material extraction, fuel production, etc.). However, the upstream processes contribute greatly to water emissions listed in **Appendix B, p. 304.2–304.6** (online only at <http://dx.doi.org/10.1065/lca2004.09.176>).

The United States Environmental Protection Agency (USEPA) has reported the annual inventory of US greenhouse gas

**Table 6:** Fossil fuel and non-renewable energy used in generating 1 MJe of electricity

| | Coal** [g $MJe^{-1}$] | Crude oil [g $MJe^{-1}$] | Natural gas [g $MJe^{-1}$] | Non-renewable energy [MJ $MJe^{-1}$] |
|---|---|---|---|---|
| ASCC | 20.78 | 6.82 | 43.39 | 3.15 |
| ECAR | 104.4 | 1.32 | 2.16 | 3.24 |
| ERCOT | 69.61 | 1.67 | 27.18 | 3.15 |
| FRCC | 38.56 | 14.16 | 13.65 | 3.13 |
| HICC | 24.22 | 47.41 | 3.54 | 3.11 |
| MAAC | 42.70 | 2.42 | 5.07 | 2.93 |
| MAIN | 82.09 | 0.94 | 1.74 | 3.19 |
| MAPP | 134.2 | 1.35 | 1.09 | 3.02 |
| NPCC | 17.12 | 8.51 | 14.21 | 2.54 |
| OFF-G | 0.61 | 0.22 | 88.38 | 4.97 |
| SERC | 65.76 | 1.55 | 5.54 | 3.03 |
| SPP | 112.4 | 1.39 | 15.37 | 3.33 |
| WSCC | 46.01 | 0.63 | 12.03 | 2.11 |
| US overall | 68.91 | 2.58 | 8.93 | 2.91 |

** Coal includes bituminous coal, sub-bituminous coal and lignite

**Table 7:** Selected environmental burdens associated with generating electricity in the United States

| | $CO_2$ [g MJe$^{-1}$] | $CH_4$ [g MJe$^{-1}$] | Hg [µg MJe$^{-1}$] | NOx [g MJe$^{-1}$] | $N_2O$ [mg MJe$^{-1}$] | Particulates [g MJe$^{-1}$] | SOx [g MJe$^{-1}$] |
|---|---|---|---|---|---|---|---|
| ASCC | 178.56 | 0.68 | 0.58 | 0.76 | 2.17 | 0.12 | 0.19 |
| ECAR | 250.66 | 0.32 | 5.71 | 0.66 | 4.04 | 1.54 | 1.55 |
| ERCOT | 190.70 | 0.54 | 2.63 | 0.40 | 53.67 | 0.21 | 0.33 |
| FRCC | 161.98 | 0.35 | 1.21 | 0.41 | 2.63 | 0.50 | 0.58 |
| HICC | 221.09 | 0.14 | 0.93 | 0.70 | 3.08 | 0.49 | 0.65 |
| MAAC | 140.54 | 0.23 | 4.34 | 0.32 | 1.97 | 0.93 | 0.94 |
| MAIN | 174.87 | 0.22 | 5.23 | 0.43 | 2.76 | 0.46 | 0.70 |
| MAPP | 236.28 | 0.28 | 5.02 | 0.56 | 58.06 | 0.38 | 0.63 |
| NPCC | 121.55 | 0.28 | 0.91 | 0.21 | 1.56 | 0.43 | 0.50 |
| OFF-G | 249.41 | 1.31 | 0.34 | 0.57 | 2.00 | 0.02 | 0.01 |
| SERC | 181.18 | 0.28 | 2.25 | 0.52 | 2.69 | 0.59 | 0.65 |
| SPP | 259.88 | 0.45 | 2.84 | 0.67 | 18.22 | 0.37 | 0.66 |
| WSCC | 135.35 | 0.29 | 1.77 | 0.39 | 2.03 | 0.19 | 0.27 |
| US weighted average | 183.10 | 0.31 | 3.30 | 0.47 | 10.20 | 0.64 | 0.75 |

**Table 8:** Gate-to-gate emissions of power plants in the overall United States electricity system in 2000

| | Unit | This study | USEPA [11] | eGRID model [2] | USEIA [9] |
|---|---|---|---|---|---|
| $CO_2$ | Tg | 2,404.19 | 2,280.70 | 2,406.67 | 2,327.87 |
| NOx | Tg | 5.84 | – | 5.12 | 5.19 |
| SOx | Tg | 10.16 | – | 10.44 | 10.68 |

emissions [11]. The USEPA report also includes GHG emissions associated with each industrial sector, including the electricity system. The United States Energy Information Administration (EIA) also reported carbon dioxide, nitrogen oxides and sulfur oxides released from the combustion process in the US electricity generation [9]. We compared the values of gate-to-gate emissions associated with power plants estimated in this study to values from USEPA and EIA reports, and the eGRID model. Results are summarized in **Table 8**. Differences between these values are less than 13%. For $CO_2$ and $SO_x$, the values estimated in this study are very close to the values reported by the US government. The relative large difference for $NO_x$ could be due to using a regional average emission value of $NO_x$ for each type of power plant in the calculations.

Total annual $CO_2$ emissions associated with the electricity system in the United States are 2,522 Tg (Tg = $10^{12}$ g), accounting for 43% of the total $CO_2$ emissions in the United States in 2000 (5,883 Tg) [11]. The overall US electricity system in 2000 released 6.54 Tg and 10.32 Tg of $NO_x$ and $SO_x$, respectively.

Uncertainties in the LCI of the electricity systems estimated here may also occur in the upstream processes (i.e., fuel extraction and manufacturing, transportation processes particularly for petroleum oil and natural gas and nuclear power plants). Information on these processes is primarily taken from commercial LCA databases due to the lack of specific information. However, the contributions from these processes are very small compared to the combustion processes in a fossil fuel-fired power plant and thus lack of specific information does not seriously affect the LCI results.

### 3.2 Greenhouse gas emissions

The greenhouse gas (GHG) emission rate in the US electricity system is about 193 g $CO_2$ eq. MJe$^{-1}$ and ranges from 128 to 277 g $CO_2$ eq. MJe$^{-1}$ in the regions (based on 100-year global warming potential). The lowest rate of GHG emission per 1 MJe of electricity occurs in the NPCC region because of a lower percentage in the fuel mix of coal-fired power plants and a higher percentage in the fuel mix of nuclear power plants. The highest value occurs in off-grid non-utility power plants because of large $CH_4$ emissions during the upstream processes. The SPP region has the second highest greenhouse gas emissions due to a higher percentage of sub-bituminous coal-fired power plants (61%) in the fuel mix.

Most greenhouse gases are released during combusting fossil fuels in the power plants, accounting for 78–95% of the total. The GHG emissions associated with the upstream processes (i.e., fuel extraction and transportation) account for over 20% of the total GHG emissions in natural gas-fired power plants due to $CO_2$ and $CH_4$ emissions during extraction and transportation, while less than 10% of the total GHG emissions in coal-fired and petroleum oil-fired power plants are associated with the upstream processes.

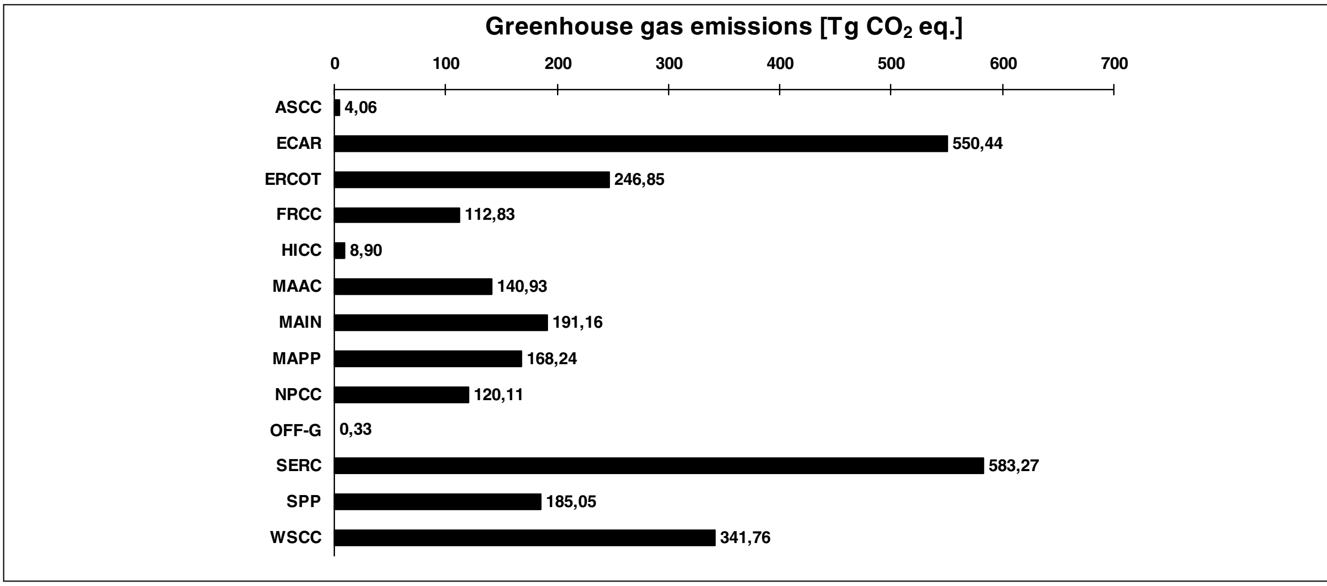


**Fig. 2:** Greenhouse gas emissions released from the US electricity generation in 2000

The overall US electricity system in 2000 released about 2,654Tg $CO_2$ eq. of greenhouse gas emissions. The greenhouse gas emissions released from coal-fired power plants account for 81% of the total GHG associated with the electricity system, and natural gas-fired power plants contribute about 16% of the total. The regions contributing most to the total GHG emissions are SERC and ECAR, which account for 22% and 21% of the total, respectively. The regional greenhouse gas emissions are illustrated in **Fig. 2**.

### 3.3 Sensitivity analysis

Thus far all values reported are based on electricity generation, in which the functional unit is to generate 1 MJe of electricity in each region. Each region in the generation-based calculations is regarded as a closed system, in which no electricity exchanges occur between the adjacent regions. In this section, a sensitivity analysis is carried out to estimate effects on the LCI of the regional electricity system when electricity exchanges between the adjacent regions are taken into account in calculating the LCI of the regional electricity system. The functional unit in this approach is defined as 1 MJe of electricity consumed in a region.

Although the exchange rates vary with the year, the exchanges in 1998 are used to estimate the life cycle inventory of the regional electricity system based on consumption in 2000 due to the lack of information on the exchange rates in 2000. The sensitivity of the exchange rate on the LCI is scrutinized by comparing the exchange rate of 1998 to the exchange rate of 1997. Each region in the United States, except for ASCC and HICC, imports (exports) electricity from (to) the adjacent regions. The total quantity of electricity under exchange is about 244 TWh (tera-Wh = $10^9$ kWh), accounting for 6.8% of the total generation in these regions in 1998 and 264 TWh (7.3%) in 1997 [2]. The exchange rates do not include the exchanges between the United States and Canada or Mexico, and the relatively small international exchange rates are not taken into account in this analysis [1].

The exporting regions in which the exportation rate is greater than the importation rate are ECAR, MACC, MAPP and SERC. The ECAR region exchanges electricity with MACC, MAIN and SERC as seen in **Table 9**. There is no exported electricity in the NPCC region, in which electricity is imported from only the MAAC region. The MAIN and MAPP regions show over 9% difference between the generation and the consumption, while other regions have less than 5%

**Table 9:** Exchange rate of electricity between the NERC regions in 1998 [2] (Unit: TWh)

| Importing region | Exporting region | | | | | | | | | | Import total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ECAR | ERCOT | FRCC | MAAC | MAIN | MAPP | NPCC | SERC | SPP | WSCC | |
| ECAR | | | | 4.82 | 3.77 | | | 31.23 | | | 39.82 |
| ERCOT | | | | | | | | | 1.19 | | 1.19 |
| FRCC | | | | | | | | 14.13 | | | 14.13 |
| MAAC | 11.06 | | | | | | | 1.31 | | | 12.37 |
| MAIN | 17.68 | | | | | 22.77 | | 13.68 | 0.87 | | 55.00 |
| MAPP | | | | | 12.34 | | | 0.66 | 2.09 | 0.37 | 15.46 |
| NPCC | | | | 10.58 | | | | | | | 10.58 |
| SERC | 28.26 | | 6.37 | 1.25 | 9.89 | 2.28 | | | 18.92 | | 66.96 |
| SPP | | 1.00 | | | 0.77 | 6.44 | | 17.49 | | 0.47 | 26.16 |
| WSCC | | | | | | 0.68 | | | 1.14 | | 1.82 |
| Export Total | 57.00 | 1.00 | 6.37 | 16.65 | 26.76 | 32.16 | 0.00 | 78.50 | 24.22 | 0.84 | |

**Table 10:** Exchange rate of the type of electricity between the NERC regions in 1998 [2]

| | Type of power plant | | | | | Fraction of the regional generation rate [%] |
|---|---|---|---|---|---|---|
| | Coal** | Petroleum oil | Natural gas | Nuclear | Hydro-electric | |
| **Import [GWh]** | | | | | | |
| ECAR | 18,151 | 1,141 | 789.70 | 18,501 | 1,233 | 6.78 |
| ERCOT | 816.39 | 0.65 | 371.34 | – | 5.11 | 0.72 |
| FRCC | 10,139 | 58.41 | 368.04 | 3,077 | 489.61 | 27.36 |
| MAAC | 11,068 | 59.12 | 59.22 | 1,167 | 14.22 | 8.02 |
| MAIN | 46,432 | 169.25 | 544.13 | 6,035 | 1,823 | 17.48 |
| MAPP | 8,578 | 87.69 | 291.01 | 5,949 | 556.24 | 2.81 |
| NPCC | 1,789 | 597.31 | 59.72 | 7,817 | 319.71 | 4.12 |
| SERC | 48,031 | 2,476 | 6,050 | 6,708 | 3,699 | 8.08 |
| SPP | 16,066 | 739.69 | 4,487 | 4,508 | 363.56 | 14.95 |
| WSCC | 1,188 | 0.87 | 373.82 | – | 258.00 | 0.38 |
| **Export [GWh]** | | | | | | |
| ECAR | 55,894 | 75.54 | 190.75 | 635.43 | 202.77 | 9.15 |
| ERCOT | 376.23 | 0.43 | 627.14 | – | 0.76 | 0.14 |
| FRCC | 69.08 | 2,183 | 1,974 | 2,140 | – | 3.85 |
| MAAC | 2,815 | 939.78 | 93.96 | 12,298 | 503.02 | 5.52 |
| MAIN | 15,552 | 223.49 | 387.67 | 10,098 | 501.50 | 5.74 |
| MAPP | 25,937 | 91.36 | 487.79 | 4,6156 | 1,034 | 23.00 |
| NPCC | – | – | – | – | – | – |
| SERC | 47,047 | 1,753 | 4,983 | 21,844 | 2,875 | 14.18 |
| SPP | 14,038 | 63.19 | 4,644 | 2,130 | 3,340 | 12.32 |
| WSCC | 530.95 | 1.04 | 5.20 | – | 305.74 | 0.26 |

** Coal includes bituminous coal, sub-bituminous coal and lignite

difference. Thus, exchanging electricity between the adjacent regions may affect the fuel mix and the environmental profile of their electricity systems based on consumption.

The exchange rates of each type of power plant between the NERC regions in 1998 are summarized in **Table 10**, in which the exchanges within a region are not taken into account. The overall fuel mixes of electricity companies are used instead of the fuel mix of individual power plants because of the characteristics of the information given by the eGRID model. Electricity from coal-fired power plants contributes about 67% of the total exchanges in the United States, followed by electricity from nuclear power plants, accounting for 22%.

With the above information, the LCI of electricity based on consumption in each region can be estimated. The fuel mix and selected environmental profiles based on consumption are summarized in **Table 11**. There are no significant changes in the fuel mix and the environmental burdens between generation-based data and consumption-based data in the

**Table 11:** Fuel mix and selected environmental profiles in the regional electricity systems (based on consumption)

| | Fuel mix [%] | | | | | | Environmental profile [g $MJe^{-1}$] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Coal** | Natural gas | Petroleum oil | Nuclear | Hydro-electric | Others* | $CO_2$ | NOx | SOx | Hg [µg] |
| ECAR | 83.26 | 2.91 | 0.71 | 11.43 | 0.63 | 1.05 | 240.68 | 0.63 | 1.46 | 5.39 |
| ERCOT | 35.01 | 50.42 | 0.86 | 11.97 | 0.17 | 1.57 | 190.96 | 0.40 | 0.33 | 2.63 |
| FRCC | 39.48 | 21.15 | 16.65 | 17.31 | 0.26 | 5.15 | 167.44 | 0.43 | 0.60 | 1.36 |
| MAAC | 48.33 | 8.77 | 2.52 | 35.92 | 1.05 | 3.41 | 150.80 | 0.35 | 1.00 | 4.57 |
| MAIN | 60.39 | 2.42 | 0.32 | 34.52 | 1.29 | 1.07 | 187.22 | 0.46 | 0.76 | 5.19 |
| MAPP | 73.00 | 1.11 | 0.52 | 14.07 | 9.16 | 2.14 | 227.35 | 0.54 | 0.62 | 4.92 |
| NPCC | 17.06 | 23.76 | 12.52 | 27.17 | 12.46 | 7.02 | 119.23 | 0.21 | 0.49 | 0.94 |
| SERC | 55.49 | 10.46 | 1.52 | 27.16 | 2.49 | 2.87 | 184.33 | 0.52 | 0.68 | 2.43 |
| SPP | 68.61 | 22.58 | 0.79 | 6.05 | 0.60 | 1.36 | 259.60 | 0.67 | 0.67 | 2.95 |
| WSCC | 32.16 | 23.33 | 0.59 | 11.09 | 28.16 | 4.67 | 135.59 | 0.39 | 0.27 | 1.78 |

** Coal includes bituminous coal, sub-bituminous coal and lignite
* Others include renewable, wind, solar and other fossil energy

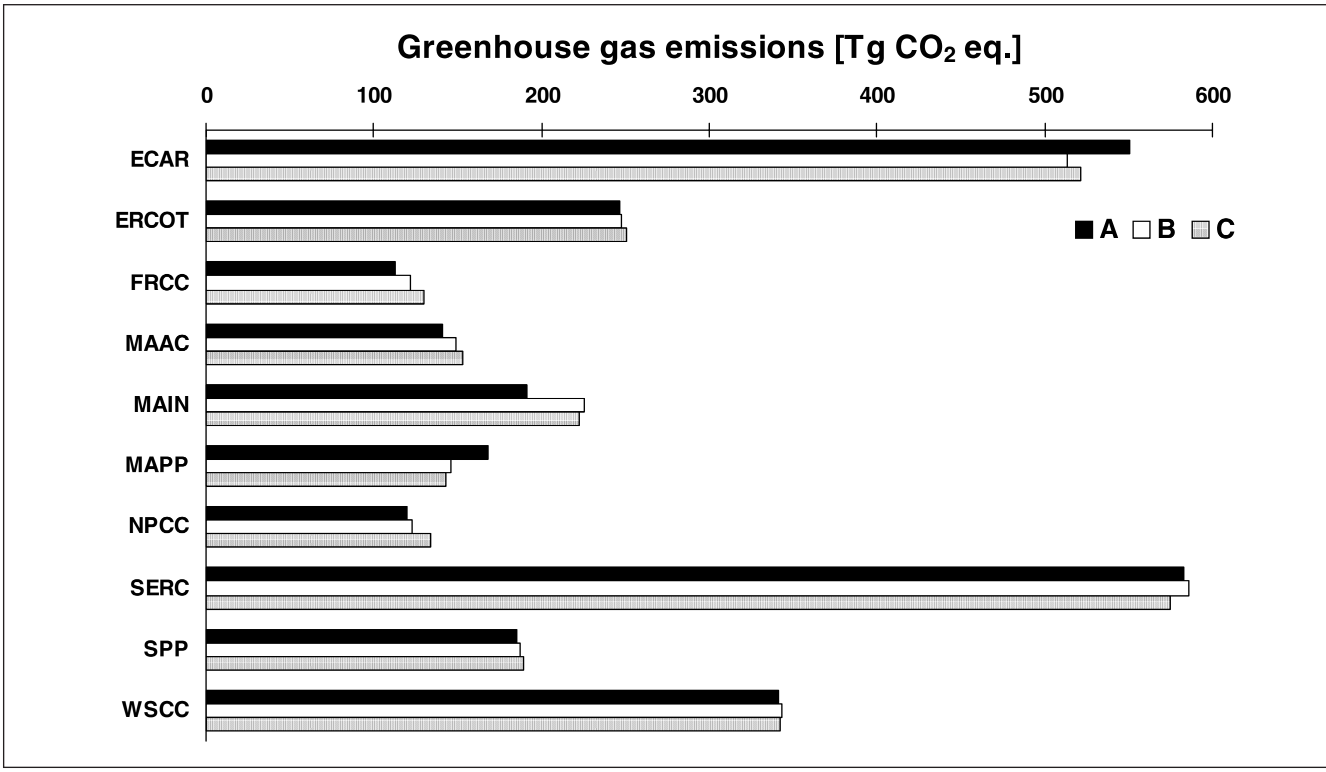


**Fig. 3:** Total greenhouse gas emissions in the regional electricity system [A: based on generation, B: based on consumption using the exchange rates in 1998, C: based on consumption using the exchange rates in 1997]

ERCOT, NPCC, SERC, SPP and WSCC regions even though the exchange rate in some regions is more than 5% of the total regional generation. This is due to the fact that the net exchange rate of each type of power plant is relatively small. In ECAR and MAPP, the consumption of electricity from coal-fired power plants is decreased by 7% and 10% respectively, compared to the generation of electricity from coal-fired power plants because more electricity from coal-fired power plants is exported to the adjacent regions. The environmental profiles based on the consumption in the ECAR, MAPP and NPCC regions are less than values based on generation. The fraction of electricity from coal-fired power plants in these four regions deceases due to exporting electricity from coal-fired power plants to the adjacent regions. The exchange rates in the regions, which have large differences of the fuel mix in generation-based and consumption-based information, lead to high sensitivity with respect to the final results.

As mentioned previously, the exchange rates in 1998 are used because the rates in 2000 are unavailable at this time. We used the exchange rates in 1997 to estimate the sensitivity to the exchange rates in the environmental profiles of electricity based on consumption. Results show that yearly variations of the exchange rates in most of regions except for the FRCC and MAPP regions do not alter the environmental profiles, even though the yearly variation of the exchange rates in some regions is large. In the FRCC and MAPP regions, the quantity of the exchanged electricity is relatively high, and the yearly variation is also large. The yearly variation of the exchange rates leads to high sensitivity with respect to the final results.

The total GHG emissions associated with the electricity system in the ECAR region are 550 Tg $CO_2$ eq. based on generation, 513 Tg $CO_2$ eq. based on consumption in 1998 and 521 Tg $CO_2$ eq. based on consumption in 1997. In the MAPP region, the total GHG emissions of electricity based on consumption are less than those based on generation. Thus these regions exported more electricity from coal-fired power plants to the adjacent regions. However, other regions have more GHG emissions released based on consumption than based on generation. The total GHG emissions resulting from the sensitivity analysis are presented in **Fig. 3**. The sensitivity analysis indicates that the environmental profiles of electricity based on consumption are more uncertain than those based on generation unless data from the same year on exchanges are available because the exchange rates vary significantly with year to year.

## 4 Conclusions and Outlook

The life cycle inventory of the US electricity system in 2000 is calculated by combining the eGRID model and DEAM™ LCA database. Those who are interested in the LCI data of the US electricity system can refer to the on-line version of this paper. When the inventory data presented in the on-line version are used in a life cycle assessment study, the distribution and transmission losses should be taken into account, which is about 9.5% of the net generation [1]. The comprehensive technical information presented in this study can be used in estimating the environmental burdens when new information on the regional fuel mix or the upstream processes is available.

The sensitivity analysis shows that the environmental profiles of electricity based on consumption are more uncertain than those based on generation unless data from the same year on exchanges are available because the exchange rates vary significantly with year to year. Thus, the generation-based LCI should be used in a LCA study unless the regional exchange rate of electricity in the same year of the generation data is available.

The exchange rates in Tables 9 and 10 offer useful information in consequential LCI studies, which describe effects on the environmental burdens by changes in the life cycle [12]. If an electricity-intensive process in a plant is built in a particular region, the region demands more electricity than what is currently consumed due to this new plant and imports more electricity from (or exports less electricity to) the adjacent regions. Thus one might estimate the environmental burdens associated with electricity consumed in a new process by using the consumption based fuel mix of the regional electricity system.

**Acknowledgements.** The authors gratefully acknowledge support provided by DuPont Biobased Materials, Inc. (Wilmington, Delaware, USA), by Cargill Dow, LLP (Minnetonka, Minnesota, USA) and by the Center for Plant Products and Technologies at Michigan State University (East Lansing, Michigan, USA).

## References

[1] Energy Information Administration (2003): Annual energy review. US Department of Energy. Washington, DC, USA <http://www.eia.doe.gov/emeu/aer/contents.html>

[2] US Environmental Protection Agency (2003): EGRID model 2002. US Environmental Protection Agency. Washington, DC, USA <http://www.epa.gov/cleanenergy/eGRID_model.htm>

[3] Ecobilan: DEAM™ LCA database. France

[4] Energy Information Administration (2004): Monthly cost and quality of fuels for electric plants data form FERC-423 database. US Department of Energy. Washington, DC, USA

[5] Energy Information Administration (2004): The coal transportation rate database. US Department of Energy. Washington, DC, USA

[6] U.S. Census Bureau (1999): 1997 Commodity flow survey in Alaska. In 1997 Economic Census. US Department of Commerce. EC97TCF-AK. Washington, DC, USA

[7] U.S. Census Bureau (1999): 1997 Commodity flow survey in Hawaii. In 1997 Economic Census. US Department of Commerce. EC97TCF-HI. Washington, DC, USA

[8] Energy Information Administration (2000): Coal industry annual 2000. US Department of Energy. DOE/EIA-0584 (2000). Washington, DC, USA

[9] Energy Information Administration (2003): Electric power annual 2002. US Department of Energy. DOE/EIA-0348 (2002). Washington, DC, USA (website: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html)

[10] US Environmental Protection Agency (2004): Compilation of air pollutant emission factors, AP-42. US Environmental Protection Agency. Washington, DC, USA <http://www.epa.gov/ttn/chief/ap42/>

[11] US Environmental Protection Agency (2003): Inventory of U.S. greenhouse gas emissions and sinks: 1990–2001. US Environmental Protection Agency. EPA 430-R-03-004. Washington, DC, USA

[12] Ekvall T, Weidema BP (2004): System boundaries and input data in consequential life cycle inventory analysis. Int J LCA 9 (3) 161–171

Received: April 8th, 2004
Accepted: September 22nd, 2004
**OnlineFirst: September 23rd, 2004**

***[12] Int J LCA 9 (3) 161–171 (2004)***

## System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis

**Tomas Ekvall[1]* and Bo P. Weidema[2]**

[1] Energy Systems Technology Division, Chalmers University of Technology, SE-412 96 Göteborg, Sweden
[2] 2.-0 LCA consultants, Amagertorv 3, 2., DK-1160 København K, Denmark

* **Corresponding author** (tomas.ekvall@me.chalmers.se)

**DOI: http://dx.doi.org/10.1065/lca2004.03.148**

**Abstract**

**Goal, Scope and Background.** A consequential life cycle assessment (LCA) is designed to generate information on the consequences of decisions. This paper includes a comprehensive presentation of the consequential approach to system boundaries, allocation and data selection. It is based on a text produced within the SETAC-Europe working group on scenarios in LCA. For most of the methodological problems, we describe ideal methodological solutions as well as simplifications intended to make the method feasible in practice.

**Method.** We compile, summarize and refine descriptions of consequential methodology elements that have been presented in separate papers, in addition to methodological elements and general conclusions that have not previously been published.

**Results and Conclusions.** A consequential LCA ideally includes activities within and outside the life cycle that are affected by a change within the life cycle of the product under investigation. In many cases this implies the use of marginal data and that allocation is typically avoided through system expansion. The model resulting from a consequential life cycle inventory (LCI) also includes the alternative use of constrained production factors as well as the marginal supply and demand on affected markets. As a result, the consequential LCI model does not resemble the traditional LCI model, where the main material flows are described from raw material extraction to waste management. Instead, it is a model of causal relationships originating at the decision at hand or the decision-maker that the LCI is intended to inform.

**Keywords:** Allocation; consequential life cycle inventory analysis; input data; methodology; modelling; system boundaries

## Appendix A: Carbon dioxide emissions versus quantity of coal used in coal-fired power plant

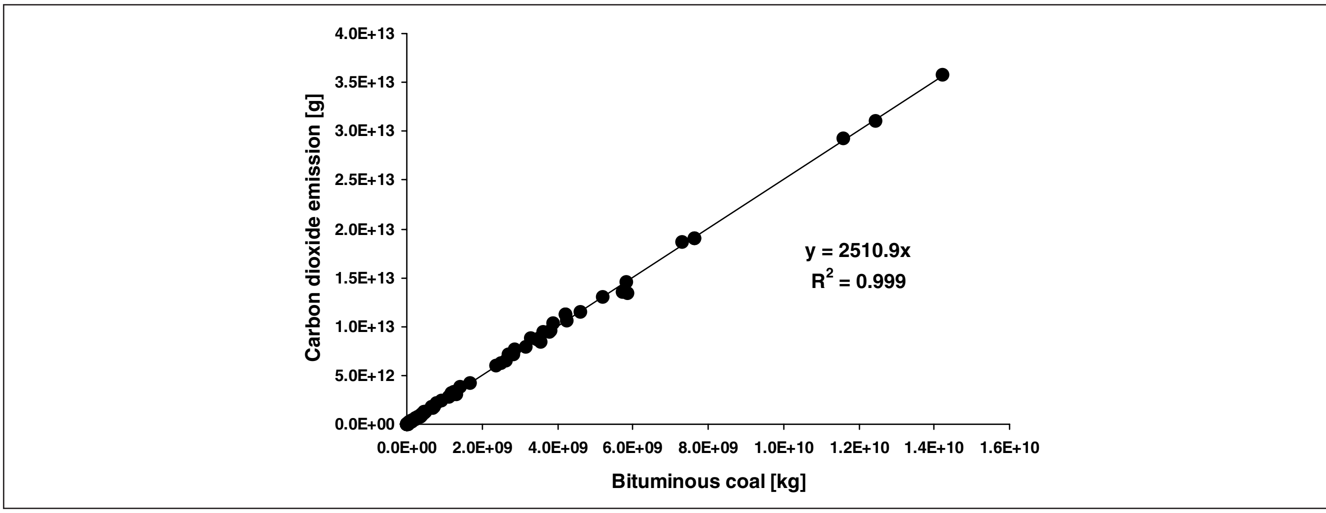


**Fig. A-1:** Carbon dioxide emissions versus quantity of bituminous coal used in the US electricity system [Solid line: linear regressed line, y: carbon dioxide emissions (g), x: amount of bituminous coal

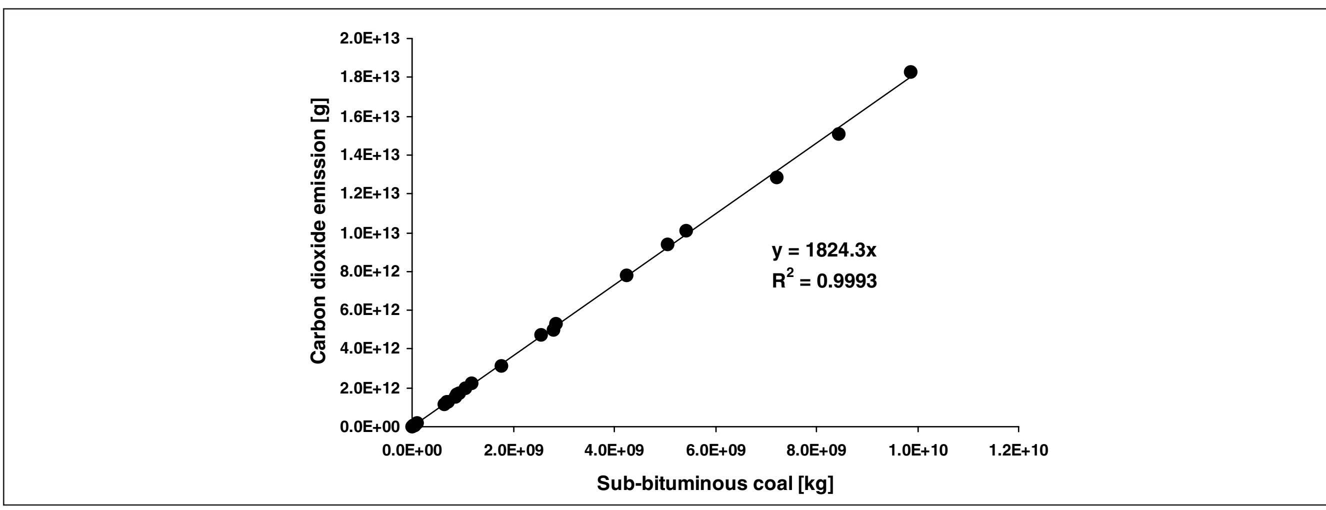


**Fig. A-2:** Carbon dioxide emissions versus quantity of sub-bituminous coal used in the US electricity system. [Solid line: linear regressed line, y: carbon dioxide emissions (g), x: amount of sub-bituminous coal (kg)]

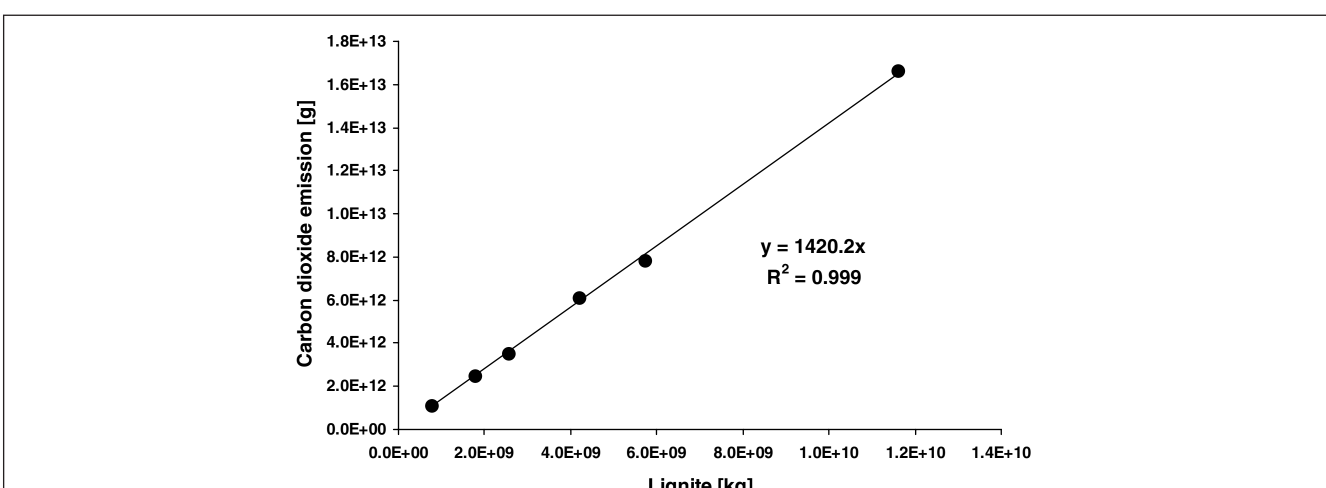


**Fig. A-3:** Carbon dioxide emissions versus quantity of lignite used in the US electricity system. [Solid line: linear regressed line, y: carbon dioxide emissions (g), x: amount of lignite (kg)]

## Appendix B: Environmental burdens associated with generating 1 MJe electricity in the United States in 2000 [based on generation]

| | Unit | US average | ASCC | ECAR | ERCOT | FRCC | HICC | MAAC | MAIN | MAPP | NPCC | OFF-G | SERC | SPP | WSCC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Resource | | | | | | | | | | | | | | | |
| Bauxite ore | kg | 1.30E-07 | 2.80E-07 | 8.46E-08 | 1.29E-07 | 5.99E-07 | 1.84E-06 | 1.06E-07 | 7.51E-08 | 1.09E-07 | 3.40E-07 | 2.34E-08 | 8.38E-08 | 1.19E-07 | 3.50E-08 |
| Coal | kg | 6.89E-02 | 2.08E-02 | 1.04E-01 | 6.96E-02 | 3.86E-02 | 2.42E-02 | 4.27E-02 | 8.21E-02 | 1.34E-01 | 1.71E-02 | 6.05E-04 | 6.58E-02 | 1.12E-01 | 4.60E-02 |
| Limestone | kg | 7.37E-03 | 5.16E-04 | 1.83E-02 | 2.32E-03 | 4.23E-03 | 3.83E-04 | 1.09E-02 | 5.71E-03 | 4.50E-03 | 4.07E-03 | 4.78E-05 | 6.86E-03 | 4.62E-03 | 2.20E-03 |
| Natural gas | kg | 8.93E-03 | 4.34E-02 | 2.16E-03 | 2.72E-02 | 1.37E-02 | 3.54E-03 | 5.07E-03 | 1.74E-03 | 1.09E-03 | 1.42E-02 | 8.84E-02 | 5.54E-03 | 1.54E-02 | 1.20E-02 |
| Oil | kg | 2.58E-03 | 6.82E-03 | 1.32E-03 | 1.67E-03 | 1.42E-02 | 4.74E-02 | 2.42E-03 | 9.43E-04 | 1.35E-03 | 8.51E-03 | 2.18E-04 | 1.55E-03 | 1.39E-03 | 6.31E-04 |
| Sand | kg | 7.99E-08 | 1.71E-07 | 5.19E-08 | 7.86E-08 | 3.68E-07 | 1.13E-06 | 6.49E-08 | 4.61E-08 | 6.68E-08 | 2.08E-07 | 1.43E-08 | 5.14E-08 | 7.27E-08 | 2.15E-08 |
| Sodium chloride | kg | 3.67E-08 | 7.86E-08 | 2.38E-08 | 3.60E-08 | 1.68E-07 | 5.18E-07 | 2.98E-08 | 2.11E-08 | 3.06E-08 | 9.51E-08 | 6.56E-09 | 2.35E-08 | 3.33E-08 | 9.87E-09 |
| Uranium ore | kg | 1.32E-06 | 8.88E-09 | 5.44E-07 | 8.05E-07 | 1.18E-06 | 2.30E-08 | 2.63E-06 | 2.62E-06 | 8.07E-07 | 1.69E-06 | 1.04E-08 | 1.91E-06 | 3.30E-07 | 7.43E-07 |
| Water used | liter | 3.69E-02 | 6.63E-02 | 3.34E-02 | 3.22E-02 | 1.46E-01 | 4.36E-01 | 3.59E-02 | 2.29E-02 | 2.85E-02 | 8.52E-02 | 5.51E-03 | 2.65E-02 | 2.96E-02 | 1.00E-02 |
| Non renewable energy | MJ | 2.91E+00 | 3.15E+00 | 3.24E+00 | 3.15E+00 | 3.13E+00 | 3.11E+00 | 2.93E+00 | 3.19E+00 | 3.02E+00 | 2.54E+00 | 4.97E+00 | 3.03E+00 | 3.33E+00 | 2.11E+00 |
| Air emissions | | | | | | | | | | | | | | | |
| Acenaphthene | g | 2.04E-08 | 7.30E-09 | 3.09E-08 | 2.17E-08 | 1.10E-08 | 6.82E-09 | 1.24E-08 | 2.41E-08 | 4.00E-08 | 5.28E-09 | 1.98E-09 | 1.89E-08 | 3.39E-08 | 1.38E-08 |
| Acenaphthylene | g | 1.67E-08 | 6.78E-09 | 2.43E-08 | 2.02E-08 | 7.27E-09 | 5.05E-09 | 8.20E-09 | 2.09E-08 | 3.71E-08 | 3.38E-09 | 1.83E-09 | 1.43E-08 | 3.15E-08 | 1.17E-08 |
| Acetaldehyde | g | 2.07E-05 | 6.37E-06 | 3.13E-05 | 2.14E-05 | 1.12E-05 | 7.19E-06 | 1.26E-05 | 2.50E-05 | 4.12E-05 | 4.99E-06 | 1.72E-07 | 1.96E-05 | 3.45E-05 | 1.39E-05 |
| Acetophenone | g | 5.15E-07 | 1.56E-07 | 7.80E-07 | 5.21E-07 | 2.88E-07 | 1.81E-07 | 3.20E-07 | 6.14E-07 | 1.00E-06 | 1.28E-07 | 4.53E-09 | 4.92E-07 | 8.40E-07 | 3.44E-07 |
| Acrolein | g | 1.01E-05 | 3.06E-06 | 1.53E-05 | 1.02E-05 | 5.61E-06 | 3.54E-06 | 6.22E-06 | 1.20E-05 | 1.97E-05 | 2.49E-06 | 8.75E-08 | 9.60E-06 | 1.66E-05 | 6.75E-06 |
| Aldehydes | g | 1.47E-04 | 1.94E-04 | 1.72E-04 | 2.40E-04 | 1.02E-04 | 1.32E-04 | 6.26E-05 | 1.60E-04 | 2.94E-04 | 7.45E-05 | 2.80E-04 | 1.06E-04 | 2.93E-04 | 1.18E-04 |
| Aluminum | g | 1.44E-07 | 3.55E-07 | 6.87E-08 | 8.71E-08 | 7.38E-07 | 5.78E-06 | 1.26E-07 | 4.91E-08 | 7.04E-08 | 4.43E-07 | 1.11E-08 | 8.06E-08 | 7.25E-08 | 3.29E-08 |
| Ammonia | g | 5.50E-04 | 2.55E-03 | 1.24E-04 | 1.70E-03 | 8.25E-04 | 1.44E-04 | 3.09E-04 | 1.03E-04 | 6.05E-05 | 8.68E-04 | 4.95E-03 | 3.44E-04 | 9.10E-04 | 7.59E-04 |
| Anthracene | g | 1.05E-08 | 4.77E-09 | 1.52E-08 | 1.24E-08 | 5.35E-09 | 3.32E-09 | 5.71E-09 | 1.26E-08 | 2.16E-08 | 2.68E-09 | 2.40E-09 | 9.33E-09 | 1.87E-08 | 7.41E-09 |
| Antimony | g | 1.95E-06 | 4.36E-06 | 1.43E-06 | 1.05E-06 | 8.80E-06 | 2.99E-05 | 1.79E-06 | 9.42E-07 | 1.48E-06 | 5.44E-06 | 3.40E-08 | 1.33E-06 | 1.24E-06 | 7.11E-07 |
| Aromatic hydrocarbons (unspecified) | g | 1.54E-10 | 3.30E-10 | 9.96E-11 | 1.51E-10 | 7.08E-10 | 2.17E-09 | 1.25E-10 | 8.87E-11 | 1.29E-10 | 4.01E-10 | 2.76E-11 | 9.87E-11 | 1.40E-10 | 4.15E-11 |
| Arsenic | g | 5.79E-05 | 1.56E-05 | 8.69E-05 | 7.49E-05 | 3.57E-05 | 2.50E-05 | 3.74E-05 | 5.97E-05 | 1.21E-04 | 1.63E-05 | 6.92E-07 | 5.41E-05 | 8.56E-05 | 3.53E-05 |
| Barium | g | 1.10E-06 | 3.81E-06 | 3.20E-07 | 1.63E-06 | 4.79E-06 | 1.45E-05 | 9.33E-07 | 1.74E-07 | 1.70E-07 | 3.29E-06 | 2.83E-06 | 6.50E-07 | 7.60E-07 | 8.02E-07 |
| Benzene | g | 3.35E-03 | 1.61E-02 | 8.65E-04 | 1.02E-02 | 5.02E-03 | 1.03E-03 | 1.90E-03 | 6.93E-04 | 4.88E-04 | 5.24E-03 | 3.29E-02 | 2.09E-03 | 5.79E-03 | 4.51E-03 |
| Benzo(a)anthracene | g | 5.71E-09 | 2.96E-09 | 8.14E-09 | 7.20E-09 | 2.68E-09 | 1.67E-09 | 2.89E-09 | 6.90E-09 | 1.21E-08 | 1.43E-09 | 1.79E-09 | 4.83E-09 | 1.06E-08 | 4.10E-09 |
| Benzo(a)pyrene | g | 3.57E-09 | 1.70E-09 | 4.35E-09 | 6.17E-09 | 4.89E-09 | 8.18E-10 | 1.68E-09 | 4.32E-09 | 6.51E-09 | 1.19E-09 | 1.18E-09 | 3.01E-09 | 6.83E-09 | 1.70E-09 |
| Benzo(b)fluoranthene | g | 4.40E-10 | 1.15E-09 | 3.07E-10 | 1.08E-09 | 4.52E-10 | 7.31E-11 | 2.27E-10 | 2.61E-10 | 4.27E-10 | 4.54E-10 | 1.75E-09 | 3.05E-10 | 7.35E-10 | 5.11E-10 |
| Benzo(bjk)fluoranthene | g | 3.78E-09 | 1.14E-09 | 5.72E-09 | 3.82E-09 | 2.12E-09 | 1.33E-09 | 2.34E-09 | 4.50E-09 | 7.36E-09 | 9.42E-10 | 3.31E-11 | 3.60E-09 | 6.17E-09 | 2.53E-09 |
| Benzo(ghi)perylene | g | 1.89E-09 | 1.30E-09 | 2.58E-09 | 2.54E-09 | 1.00E-09 | 5.44E-10 | 9.78E-10 | 2.17E-09 | 3.80E-09 | 6.09E-10 | 1.18E-09 | 1.59E-09 | 3.43E-09 | 1.43E-09 |
| Benzo(k)fluoranthene | g | 5.27E-10 | 1.19E-09 | 4.30E-10 | 1.20E-09 | 4.74E-10 | 9.51E-11 | 2.57E-10 | 3.79E-10 | 6.52E-10 | 4.63E-10 | 1.75E-09 | 3.70E-10 | 9.23E-10 | 5.72E-10 |
| Benzyl chloride | g | 2.41E-05 | 7.25E-06 | 3.64E-05 | 2.43E-05 | 1.35E-05 | 8.46E-06 | 1.49E-05 | 2.86E-05 | 4.68E-05 | 5.97E-06 | 2.11E-07 | 2.29E-05 | 3.92E-05 | 1.60E-05 |
| Beryllium | g | 6.83E-06 | 1.82E-06 | 1.04E-05 | 8.04E-06 | 4.05E-06 | 2.25E-06 | 4.44E-06 | 7.32E-06 | 1.37E-05 | 1.80E-06 | 8.37E-08 | 6.51E-06 | 1.02E-05 | 4.29E-06 |
| Bromoform | g | 1.34E-06 | 4.04E-07 | 2.03E-06 | 1.36E-06 | 7.50E-07 | 4.71E-07 | 8.30E-07 | 1.59E-06 | 2.61E-06 | 3.32E-07 | 1.18E-08 | 1.28E-06 | 2.18E-06 | 8.94E-07 |

## Appendix B: Environmental burdens associated with generating 1 MJe electricity in the United States in 2000 [based on generation] (*cont'd*)

| | | US average | ASCC | ECAR | ERCOT | FRCC | HICC | MAAC | MAIN | MAPP | NPCC | OFF-G | SERC | SPP | WSCC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Butadiene | g | 6.08E-08 | 2.40E-08 | 8.66E-08 | 8.21E-08 | 1.58E-08 | 1.55E-08 | 2.11E-08 | 8.25E-08 | 1.58E-07 | 6.31E-09 | 0.00E+00 | 4.56E-08 | 1.32E-07 | 4.31E-08 |
| Butane | g | 3.18E-04 | 1.27E-03 | 5.72E-05 | 1.01E-03 | 4.68E-04 | 3.69E-05 | 1.75E-04 | 5.36E-05 | 2.51E-05 | 4.99E-04 | 2.04E-03 | 2.05E-04 | 4.63E-04 | 4.64E-04 |
| Cadmium | g | 4.31E-06 | 1.77E-06 | 6.59E-06 | 4.26E-06 | 3.26E-06 | 3.57E-06 | 2.92E-06 | 4.65E-06 | 7.51E-06 | 1.63E-06 | 5.47E-07 | 4.18E-06 | 6.30E-06 | 2.84E-06 |
| Calcium | g | 1.25E-07 | 3.08E-07 | 5.96E-08 | 7.55E-08 | 6.39E-07 | 5.01E-06 | 1.10E-07 | 4.26E-08 | 6.10E-08 | 3.84E-07 | 9.69E-09 | 6.98E-08 | 6.29E-08 | 2.84E-08 |
| Carbon dioxide (biomass) | g | 2.97E-04 | 7.18E-04 | 1.97E-05 | 8.75E-06 | 2.92E-06 | 4.60E-05 | 5.16E-05 | 4.14E-05 | 3.58E-04 | 5.36E-04 | 2.92E-06 | 9.95E-05 | 9.33E-05 | 1.17E-03 |
| Carbon dioxide (fossil) | g | 1.83E+02 | 1.79E+02 | 2.51E+02 | 1.91E+02 | 1.62E+02 | 2.21E+02 | 1.41E+02 | 1.75E+02 | 2.36E+02 | 1.22E+02 | 2.49E+02 | 1.81E+02 | 2.60E+02 | 1.35E+02 |
| Carbon disulfide | g | 4.46E-06 | 1.35E-06 | 6.76E-06 | 4.51E-06 | 2.50E-06 | 1.57E-06 | 2.77E-06 | 5.32E-06 | 8.70E-06 | 1.10E-06 | 3.92E-08 | 4.26E-06 | 7.28E-06 | 2.98E-06 |
| Carbon monoxide | g | 5.10E-02 | 1.16E-01 | 4.39E-02 | 1.02E-01 | 6.96E-02 | 6.43E-02 | 2.98E-02 | 3.64E-02 | 5.42E-02 | 5.08E-02 | 1.90E-01 | 3.95E-02 | 8.22E-02 | 4.76E-02 |
| Chlorides | g | 8.78E-05 | 2.76E-04 | 3.28E-05 | 2.83E-05 | 5.59E-04 | 1.96E-03 | 9.33E-05 | 1.35E-05 | 1.86E-05 | 3.50E-04 | 1.88E-06 | 4.89E-05 | 1.54E-05 | 1.96E-05 |
| Chlorine | g | 1.23E-09 | 6.02E-09 | 2.97E-10 | 3.78E-09 | 1.87E-09 | 3.65E-10 | 6.98E-10 | 2.38E-10 | 1.48E-10 | 1.96E-09 | 1.23E-08 | 7.65E-10 | 2.14E-09 | 1.67E-09 |
| Chloroacetophenone | g | 2.41E-07 | 7.25E-08 | 3.64E-07 | 2.43E-07 | 1.35E-07 | 8.46E-08 | 1.49E-07 | 2.86E-07 | 4.68E-07 | 5.97E-08 | 2.11E-09 | 2.29E-07 | 3.92E-07 | 1.60E-07 |
| Chlorobenzene | g | 7.56E-07 | 2.28E-07 | 1.14E-06 | 7.63E-07 | 4.23E-07 | 2.65E-07 | 4.68E-07 | 9.00E-07 | 1.48E-06 | 1.87E-07 | 6.64E-09 | 7.22E-07 | 1.23E-06 | 5.04E-07 |
| Chloroform | g | 2.03E-06 | 6.11E-07 | 3.07E-06 | 2.05E-06 | 1.13E-06 | 7.13E-07 | 1.26E-06 | 2.42E-06 | 3.95E-06 | 5.03E-07 | 1.78E-08 | 1.94E-06 | 3.30E-06 | 1.35E-06 |
| Chromium (Cr III, Cr VI) | g | 1.07E-04 | 2.96E-05 | 1.69E-04 | 1.06E-04 | 6.71E-05 | 3.93E-05 | 7.25E-05 | 1.17E-04 | 1.94E-04 | 3.02E-05 | 1.94E-06 | 1.05E-04 | 1.56E-04 | 6.90E-05 |
| Chrysene | g | 4.28E-09 | 2.34E-09 | 6.09E-09 | 5.09E-09 | 2.48E-09 | 1.39E-09 | 2.51E-09 | 4.89E-09 | 8.15E-09 | 1.35E-09 | 1.78E-09 | 3.88E-09 | 7.20E-09 | 3.09E-09 |
| Cobalt | g | 4.99E-06 | 5.92E-06 | 5.79E-06 | 4.02E-06 | 1.17E-05 | 3.56E-05 | 3.77E-06 | 4.34E-06 | 7.03E-06 | 6.97E-06 | 1.65E-07 | 4.15E-06 | 5.90E-06 | 2.66E-06 |
| Copper | g | 5.95E-07 | 1.98E-06 | 1.96E-07 | 5.96E-07 | 3.09E-06 | 1.03E-05 | 5.59E-07 | 9.51E-08 | 1.10E-07 | 2.02E-06 | 9.14E-07 | 3.43E-07 | 2.87E-07 | 3.07E-07 |
| Cumene | g | 1.82E-07 | 5.49E-08 | 2.76E-07 | 1.84E-07 | 1.02E-07 | 6.40E-08 | 1.13E-07 | 2.17E-07 | 3.55E-07 | 4.52E-08 | 1.60E-09 | 1.74E-07 | 2.97E-07 | 1.21E-07 |
| Cyanide | g | 8.59E-05 | 2.59E-05 | 1.30E-04 | 8.67E-05 | 4.81E-05 | 3.02E-05 | 5.32E-05 | 1.02E-04 | 1.67E-04 | 2.13E-05 | 7.54E-07 | 8.19E-05 | 1.40E-04 | 5.73E-05 |
| Di(2-ethylhexyl)phthalate | g | 2.51E-06 | 7.56E-07 | 3.80E-06 | 2.53E-06 | 1.40E-06 | 8.82E-07 | 1.56E-06 | 2.99E-06 | 4.89E-06 | 6.23E-07 | 2.20E-08 | 2.39E-06 | 4.09E-06 | 1.67E-06 |
| Dibenzo(a,h)anthracene | g | 1.10E-09 | 1.09E-09 | 1.37E-09 | 1.80E-09 | 5.16E-10 | 2.53E-10 | 4.41E-10 | 1.27E-09 | 2.37E-09 | 3.90E-10 | 1.17E-09 | 8.13E-10 | 2.24E-09 | 9.14E-10 |
| Dichlorobenzene | g | 1.81E-07 | 7.22E-07 | 3.27E-08 | 5.76E-07 | 2.68E-07 | 2.11E-08 | 9.96E-08 | 3.06E-08 | 1.43E-08 | 2.85E-07 | 1.17E-06 | 1.17E-07 | 2.64E-07 | 2.65E-07 |
| Dimethyl benzanthracene | g | 2.42E-09 | 9.60E-09 | 4.34E-10 | 7.66E-09 | 3.56E-09 | 2.63E-10 | 1.33E-09 | 4.06E-10 | 1.90E-10 | 3.79E-09 | 1.55E-08 | 1.56E-09 | 3.51E-09 | 3.53E-09 |
| Dimethyl sulfate | g | 1.65E-06 | 4.97E-07 | 2.50E-06 | 1.67E-06 | 9.23E-07 | 5.79E-07 | 1.02E-06 | 1.96E-06 | 3.21E-06 | 4.09E-07 | 1.45E-08 | 1.58E-06 | 2.69E-06 | 1.10E-06 |
| Dinitrotoluene | g | 9.60E-09 | 2.90E-09 | 1.46E-08 | 9.69E-09 | 5.39E-09 | 3.39E-09 | 5.96E-09 | 1.15E-08 | 1.87E-08 | 2.39E-09 | 8.45E-11 | 9.14E-09 | 1.57E-08 | 6.42E-09 |
| Dioxins (unspecified) | g | 6.81E-10 | 2.24E-10 | 1.13E-09 | 3.04E-10 | 4.16E-10 | 2.59E-10 | 4.62E-10 | 8.89E-10 | 9.78E-10 | 1.85E-10 | 4.88E-12 | 7.13E-10 | 1.09E-09 | 4.98E-10 |
| Diphenyl | g | 5.84E-08 | 1.77E-08 | 8.85E-08 | 5.90E-08 | 3.27E-08 | 2.06E-08 | 3.62E-08 | 6.95E-08 | 1.14E-07 | 1.45E-08 | 5.12E-10 | 5.58E-08 | 9.51E-08 | 3.90E-08 |
| Ethane | g | 4.69E-04 | 1.87E-03 | 8.44E-05 | 1.49E-03 | 6.91E-04 | 5.45E-05 | 2.58E-04 | 7.91E-05 | 3.70E-05 | 7.37E-04 | 3.01E-03 | 3.02E-04 | 6.83E-04 | 6.85E-04 |
| Ethyl benzene | g | 3.24E-06 | 1.02E-06 | 4.90E-06 | 3.27E-06 | 1.91E-06 | 1.49E-06 | 2.02E-06 | 3.85E-06 | 6.29E-06 | 8.66E-07 | 2.87E-08 | 3.09E-06 | 5.27E-06 | 2.16E-06 |
| Ethyl chloride | g | 1.44E-06 | 4.35E-07 | 2.18E-06 | 1.46E-06 | 8.08E-07 | 5.07E-07 | 8.94E-07 | 1.72E-06 | 2.81E-06 | 3.59E-07 | 1.27E-08 | 1.38E-06 | 2.35E-06 | 9.60E-07 |
| Ethylene dibromide | g | 4.12E-08 | 1.24E-08 | 6.25E-08 | 4.16E-08 | 2.31E-08 | 1.45E-08 | 2.55E-08 | 4.91E-08 | 8.03E-08 | 1.02E-08 | 3.62E-10 | 3.93E-08 | 6.73E-08 | 2.75E-08 |
| Ethylene dichloride | g | 1.38E-06 | 4.15E-07 | 2.08E-06 | 1.39E-06 | 7.69E-07 | 4.83E-07 | 8.51E-07 | 1.64E-06 | 2.68E-06 | 3.41E-07 | 1.20E-08 | 1.31E-06 | 2.25E-06 | 9.14E-07 |
| Fluoranthene | g | 3.68E-08 | 1.39E-08 | 5.40E-08 | 4.21E-08 | 1.75E-08 | 1.17E-08 | 1.96E-08 | 4.52E-08 | 7.82E-08 | 8.03E-09 | 3.14E-09 | 3.25E-08 | 6.61E-08 | 2.53E-08 |
| Fluorene | g | 7.71E-08 | 2.91E-08 | 1.12E-07 | 9.42E-08 | 3.00E-08 | 2.25E-08 | 3.54E-08 | 9.87E-08 | 1.78E-07 | 1.31E-08 | 3.01E-09 | 6.42E-08 | 1.50E-07 | 5.37E-08 |

## Appendix B: Environmental burdens associated with generating 1 MJe electricity in the United States in 2000 [based on generation] (*cont'd*)

| | Unit | US average | ASCC | ECAR | ERCOT | FRCC | HICC | MAAC | MAIN | MAPP | NPCC | OFF-G | SERC | SPP | WSCC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fluorides | g | 1.05E-05 | 2.97E-05 | 3.96E-06 | 3.68E-06 | 6.10E-05 | 2.11E-04 | 1.21E-05 | 3.52E-06 | 2.63E-06 | 3.89E-05 | 2.23E-07 | 6.76E-06 | 1.92E-0 6 | 2.70E-06 |
| Formaldehyde | g | 6.21E-05 | 1.91E-04 | 2.92E-05 | 1.32E-04 | 1.53E-04 | 3.35E- 04 | 4.19E-05 | 2.25E-05 | 2.95E-05 | 1.17E-04 | 2.27E-04 | 4.18E-05 | 7.49E-05 | 6.28E-05 |
| Furan | g | 3.16E-09 | 1.04E-09 | 5.26E-09 | 1.41E-09 | 1.94E-09 | 1.20E-09 | 2.15 E-09 | 4.14E-09 | 4.53E-09 | 8.57E-10 | 2.27E-11 | 3.31E-09 | 5.07E-09 | 2.32E-09 |
| Halogenated hydrocarbons (unspecified) | g | 8.56E-16 | 1.84E-15 | 5.55E-16 | 8.41E-16 | 3.93E-15 | 1.20E-14 | 6.94E-16 | 4.93E-16 | 7.15E-16 | 2.23E-15 | 1.53E-16 | 5.50E-16 | 7.79E-16 | 2.30E-16 |
| Halon 1301 | g | 1.49E-12 | 3.20E-12 | 9.69E-13 | 1.47E-12 | 6.84E-12 | 2.10E-11 | 1.21E-12 | 8.58E-13 | 1.24E-12 | 3.87E-12 | 2.66E-13 | 9.60E-13 | 1.36E-12 | 4.00E-13 |
| Hexane | g | 2.75E-04 | 1.09E-03 | 5.25E-05 | 8.67E-04 | 4.03E-04 | 3.24E-05 | 1. 51E-04 | 4.87E-05 | 2.60E-05 | 4.28E-04 | 1.75E-03 | 1.78E-04 | 4.00E-04 | 3.99E-04 |
| Hydrocarbons (except methane) | g | 8.88E-03 | 3.15E-02 | 5.16E-03 | 2.17E-02 | 1.88E-02 | 1.64E-02 | 5.34E-03 | 3.51E-03 | 3.53E-03 | 1.28E-02 | 5.93E-02 | 6.17E-03 | 1.36E-02 | 8.87E-03 |
| Hydrocarbons (unspecified) | g | 2.31E-03 | 3.67E-03 | 1.69E-03 | 3.75E-03 | 5.33E-03 | 1.70E-02 | 1.14E-03 | 2.22E-03 | 4.97E-03 | 3.26E-03 | 1.62E-03 | 1.36E-03 | 4.02E-03 | 1.27E-03 |
| Hydrogen chloride | g | 4.13E-02 | 1.24E-02 | 6.25E-02 | 4.17E-02 | 2.31E-02 | 1.45E-02 | 2.56E-02 | 4.92E-02 | 8.04E-02 | 1.02E-02 | 3.62E-04 | 3.94E-02 | 6.73E-02 | 2.76E-02 |
| Hydrogen fluoride | g | 5.16E-03 | 1.56E-03 | 7.82E-03 | 5.21E-03 | 2.89E-03 | 1.81E-03 | 3.20E-03 | 6.15E-03 | 1.01E-02 | 1.28E-03 | 4.53E-05 | 4.92E-03 | 8.42E-03 | 3.45E-03 |
| Hydrogen sulfide | g | 2.11E-05 | 5.58E-05 | 1.08E-05 | 1.37E-05 | 1.16E-04 | 3.88E-04 | 1.98E-05 | 7.70E-06 | 1.10E-05 | 6.96E-05 | 1.75E-06 | 1.27E-05 | 1.14E-05 | 5.16E-06 |
| Indeno (1,2,3,c,d) pyrene | g | 2.97E-09 | 1.95E-09 | 4.11E-09 | 3.78E-09 | 1.74E-09 | 9.23E-10 | 1.68E-09 | 3.34E-09 | 5.62E-09 | 1.02E-09 | 1.77E-09 | 2.63E-09 | 5.09E-09 | 2.22E-09 |
| Iron | g | 2.79E-07 | 6.86E-07 | 1.33E-07 | 1.68E-07 | 1.43E-06 | 1.11E-05 | 2.44 E-07 | 9.51E-08 | 1.36E-07 | 8.56E-07 | 2.15E-08 | 1.56E-07 | 1.40E-07 | 6.35E-08 |
| Isophorone | g | 1.99E-05 | 6.01E-06 | 3.01E-05 | 2.01E-05 | 1.11E-05 | 7.01E-06 | 1.23E-05 | 2.37E-05 | 3.88E-05 | 4.94E-06 | 1.75E-07 | 1.90E-05 | 3.25E-05 | 1.33E-05 |
| Lead | g | 7.05E-05 | 2.41E-05 | 1.14E-04 | 3.98E-05 | 4.46E-05 | 3.49E-05 | 4.72 E-05 | 8.99E-05 | 1.08E-04 | 2.03E-05 | 9.23E-07 | 7.22E-05 | 1.13E-04 | 5.05E-05 |
| Magnesium | g | 3.78E-04 | 1.14E-04 | 5.73E-04 | 3.82E-04 | 2.12E-04 | 1.33E-04 | 2.34E-04 | 4.51E-04 | 7.37E-04 | 9.39E-05 | 3.32E-06 | 3.61E-04 | 6.17E-04 | 2.53E-04 |
| Manganese | g | 1.23E-04 | 3.56E-05 | 1.98E-04 | 1.11E-04 | 8.10E-05 | 5.53E-05 | 8.52E-05 | 1.36E-04 | 2.13E-04 | 3.68E-05 | 1.57E-06 | 1.24E-04 | 1.79E-0 4 | 8.07E-05 |
| Mercury | g | 3.30E-06 | 5.83E-07 | 5.71E-06 | 2.63E-06 | 1.21E-06 | 9.33E-07 | 4. 34E-06 | 5.23E-06 | 5.02E-06 | 9.05E-07 | 3.37E-07 | 2.25E-06 | 2.84E-06 | 1.77E-06 |
| Metals (unspecified) | g | 2.14E-09 | 7.96E-09 | 8.83E-10 | 4.66E-09 | 6.01E-09 | 1.31E-08 | 1.43E-09 | 7.58E-10 | 9.03E-10 | 4.30E-09 | 1.25E-08 | 1.35E-09 | 2.96E-09 | 1.92E-09 |
| Methane | g | 3.13E-01 | 6.85E-01 | 3.19E-01 | 5.37E-01 | 3.50E-01 | 1.45E-01 | 2. 25E-01 | 2.18E-01 | 2.79E-01 | 2.78E-01 | 1.31E+00 | 2.83E-01 | 4.47E-01 | 2.93E-01 |
| Methyl bromide | g | 5.50E-06 | 1.66E-06 | 8.33E-06 | 5.55E-06 | 3.08E-06 | 1.93 E-06 | 3.40E-06 | 6.55E-06 | 1.07E-05 | 1.37E-06 | 4.83E-08 | 5.24E-06 | 8.96E-06 | 3.67E-06 |
| Methyl chloride | g | 1.82E-05 | 5.49E-06 | 2.76E-05 | 1.84E-05 | 1.02E-05 | 6. 40E-06 | 1.13E-05 | 2.17E-05 | 3.55E-05 | 4.52E-06 | 1.60E-07 | 1.74E-05 | 2.97E-05 | 1.21E-05 |
| Methyl cholanthrene | g | 2.73E-10 | 1.09E-09 | 4.90E-11 | 8.65E-10 | 4.01E-10 | 3.16E-11 | 1.50E-10 | 4.60E-11 | 2.15E-11 | 4.28E-10 | 1.75E-09 | 1.76E-10 | 3.97E-10 | 3.98E-10 |
| Methyl chrysene | g | 7.56E-10 | 2.28E-10 | 1.14E-09 | 7.63E-10 | 4.23E-10 | 2.65E-10 | 4.68E-10 | 9.00E-10 | 1.48E-09 | 1.87E-10 | 6.64E-12 | 7.22E-10 | 1.23E-09 | 5.04E-10 |
| Methyl ethyl ketone | g | 1.34E-05 | 4.04E-06 | 2.03E-05 | 1.36E-05 | 7.50E-06 | 4.71E-06 | 8.30E-06 | 1.59E-05 | 2.61E-05 | 3.32E-06 | 1.18E-07 | 1.28E-05 | 2.18E-05 | 8.94E-06 |
| Methyl hydrazine | g | 5.84E-06 | 1.77E-06 | 8.85E-06 | 5.90E-06 | 3.27E-06 | 2.06E-06 | 3.62E-06 | 6.95E-06 | 1.14E-05 | 1.45E-06 | 5.12E-08 | 5.58E-06 | 9.51E-06 | 3.90E-06 |
| Methyl methacrylate | g | 6.87E-07 | 2.07E-07 | 1.04E-06 | 6.94E-07 | 3.85E-07 | 2.42E-07 | 4.26E-07 | 8.18E-07 | 1.34E-06 | 1.70E-07 | 6.03E-09 | 6.55E-07 | 1.12E-06 | 4.59E-07 |
| Methyl naphthalene | g | 3.63E-09 | 1.45E-08 | 6.54E-10 | 1.15E-08 | 5.35E-09 | 4.22E-10 | 2.00E-09 | 6.13E-10 | 2.87E-10 | 5.70E-09 | 2.33E-08 | 2.34E-09 | 5.29E-09 | 5.31E-09 |
| Methyl tert butyl ether (MTBE) | g | 1.20E-06 | 3.63E-07 | 1.82E-06 | 1.21E-06 | 6.73E-07 | 4.23E-07 | 7.45E-07 | 1.43E-06 | 2.34E-06 | 2.99E-07 | 1.06E-08 | 1.15E-06 | 1.96E-06 | 8.03E-07 |
| Methylene chloride | g | 9.96E-06 | 3.01E-06 | 1.51E-05 | 1.00E-05 | 5.58E-06 | 3.50E-06 | 6.17E-06 | 1.19E-05 | 1.94E-05 | 2.47E-06 | 8.75E-08 | 9.51E-06 | 1.62E-05 | 6.65E-06 |
| Molybdenum | g | 3.86E-07 | 1.35E-06 | 1.11E-07 | 6.26E-07 | 1.58E-06 | 4.93E-06 | 3.18E-07 | 6.41E-08 | 6.17E-08 | 1.10E-06 | 1.12E-06 | 2.30E-07 | 2.95E-07 | 3.02E-07 |
| Naphthalene | g | 9.60E-07 | 1.46E-06 | 9.87E-07 | 1.01E-06 | 2.25E-06 | 6.58E-06 | 6.77E-07 | 7.70E-07 | 1.28E-06 | 1.41E-06 | 6.03E-07 | 7.44E-07 | 1.20E-06 | 5.90E-07 |

**Appendix B: Environmental burdens associated with generating 1 MJe electricity in the United States in 2000 [based on generation] (*cont'd*)**

| | Unit | US average | ASCC | ECAR | ERCOT | FRCC | HICC | MAAC | MAIN | MAPP | NPCC | OFF-G | SERC | SPP | WSCC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nickel | g | 1.11E-04 | 9.40E-05 | 1.52E-04 | 8.40E-05 | 1.95E-04 | 5.34E-04 | 8.45E-05 | 1.03E-04 | 1.55E-04 | 1.12E-04 | 2.82E-06 | 1.02E-04 | 1.33E-04 | 6 .36E-05 |
| Nitrogen oxides (NOx) | g | 4.75E-01 | 7.62E-01 | 6.56E-01 | 3.98E-01 | 4.06E-01 | 7.02E-01 | 3.23E-01 | 4.26E-01 | 5.56E-01 | 2.09E-01 | 5.73E-01 | 5.19E-01 | 6.70E-01 | 3.86E-01 |
| Nitrous oxide | g | 1.02E-02 | 2.17E-03 | 4.04E-03 | 5.37E-02 | 2.63E-03 | 3.08E-03 | 1.97E-03 | 2.76E-03 | 5.81E-02 | 1.56E-03 | 2.00E-03 | 2.69E-03 | 1.8 2E-02 | 2.03E-03 |
| Organic matter (unspecified) | g | 1.65E-02 | 8.06E-02 | 3.97E-03 | 5.05E-02 | 2.49E-02 | 5.00E-03 | 9.35E-03 | 3.19E-03 | 1.99E-03 | 2.62E-02 | 1.65E-01 | 1.02E-02 | 2.86E-02 | 2.24E-02 |
| Particulates (PM 10) | g | 4.84E-04 | 1.94E-04 | 6.87E-04 | 6.52E-04 | 1.34E-04 | 1.51E-04 | 1.68E-04 | 6.55E-04 | 1.25E-03 | 5.51E-05 | 1.29E-07 | 3.63E-04 | 1.05E-03 | 3.42E-04 |
| Particulates (unspecified) | g | 6.35E-01 | 1.16E-01 | 1.54E+00 | 2.14E-01 | 4.98E-01 | 4.88E-01 | 9.35E-01 | 4.56E-01 | 3.78E-01 | 4.27E-01 | 2.34E-02 | 5.91E-01 | 3.72E-01 | 1.89E-01 |
| Pentane | g | 3.93E-04 | 1.57E-03 | 7.08E-05 | 1.25E-03 | 5.80E-04 | 4.57E-05 | 2.16E-04 | 6.64E-05 | 3.11E-05 | 6.18E-04 | 2.53E-03 | 2.54E-04 | 5.73E-04 | 5.75E-04 |
| Phenanthrene | g | 1.41E-07 | 5.63E-08 | 2.06E-07 | 1.64E-07 | 6.77E-08 | 4.45E-08 | 7.49E-08 | 1.73E-07 | 3.00E-07 | 3.19E-08 | 1.74E-08 | 1.25E-07 | 2.54 E-07 | 9.78E-08 |
| Phenol | g | 5.50E-07 | 1.66E-07 | 8.33E-07 | 5.55E-07 | 3.08E-07 | 1.93E-07 | 3.40E-07 | 6.55E-07 | 1.07E-06 | 1.37E-07 | 4.83E-09 | 5.24E-07 | 8.96E-07 | 3 .67E-07 |
| Phosphorus | g | 2.48E-06 | 7.74E-06 | 9.33E-07 | 8.24E-07 | 1.57E-05 | 5.68E-05 | 2.62E-06 | 3.97E-07 | 5.48E-07 | 9.78E-06 | 5.79E-08 | 1.38E-06 | 4.62E- 07 | 5.55E-07 |
| Polycyclic Aromatic Hydrocarbons (PAH, unspecified) | g | 1.71E-13 | 3.67E-13 | 1.11E-13 | 1.68E-13 | 7.87E-13 | 2.42E-12 | 1.39E-13 | 9.87E-14 | 1.43E-13 | 4.45E-13 | 3.07E-14 | 1.10E-13 | 1.56E-13 | 4.60E-14 |
| Propane | g | 2.31E-04 | 9.14E-04 | 4.04E-05 | 7.38E-04 | 3.35E-04 | 2.81E-07 | 1.26E-04 | 3.83E-05 | 1.69E-05 | 3.61E-04 | 1.46E-03 | 1.49E-04 | 3.35E-04 | 3.41E-04 |
| Propionaldehyde | g | 1.30E-05 | 3.94E-06 | 1.97E-05 | 1.32E-05 | 7.31E-06 | 4.59E-06 | 8.08E-06 | 1.56E-05 | 2.54E-05 | 3.24E-06 | 1.15E-07 | 1.25E-05 | 2 .13E-05 | 8.72E-06 |
| Propylene | g | 4.01E-06 | 1.58E-06 | 5.71E-06 | 5.41E-06 | 1.05E-06 | 1.02E-06 | 1.39E-06 | 5.44E-06 | 1.04E-05 | 4.16E-07 | 0.00E+00 | 3.01E-06 | 8.71E-0 6 | 2.84E-06 |
| Pyrene | g | 1.96E-08 | 9.42E-09 | 2.80E-08 | 2.39E-08 | 9.42E-09 | 5.97E-09 | 1.00E-08 | 2.37E-08 | 4.14E-08 | 4.80E-09 | 4.96E-09 | 1.69E-08 | 3.58E-08 | 1 .39E-08 |
| Selenium | g | 4.48E-05 | 1.40E-05 | 6.77E-05 | 4.52E-05 | 2.61E-05 | 1.97E-05 | 2.79E-05 | 5.32E-05 | 8.70E-05 | 1.18E-05 | 4.19E-07 | 4.27E-05 | 7.29E-05 | 2.99E-05 |
| Silicon | g | 1.25E-07 | 3.08E-07 | 5.96E-08 | 7.55E-08 | 6.39E-07 | 5.01E-06 | 1.10E-07 | 4.26E-08 | 6.10E-08 | 3.84E-07 | 9.69E-09 | 6.98E-08 | 6.29E-08 | 2.84E-08 |
| Sodium | g | 7.40E-07 | 1.82E-06 | 3.53E-07 | 4.47E-07 | 3.78E-06 | 2.97E-05 | 6.47E-07 | 2.52E-07 | 3.61E-07 | 2.27E-06 | 5.71E-08 | 4.14E-07 | 3.72E-07 | 1 .68E-07 |
| Styrene | g | 8.59E-07 | 2.59E-07 | 1.30E-06 | 8.67E-07 | 4.81E-07 | 3.02E-07 | 5.32E-07 | 1.02E-06 | 1.67E-06 | 2.13E-07 | 7.54E-09 | 8.19E-07 | 1.40E-06 | 5.73E-07 |
| Sulfur Oxides (SOx) | g | 7.49E-01 | 1.94E-01 | 1.55E+00 | 3.31E-01 | 5.81E-01 | 6.52E-01 | 9.45E-01 | 7.01E-01 | 6.28E-01 | 4.96E-01 | 1.32E-02 | 6.52E-01 | 6.55E-01 | 2.69E-01 |
| Tetrachloroethylene | g | 1.48E-06 | 4.45E-07 | 2.24E-06 | 1.49E-06 | 8.27E-07 | 5.20E-07 | 9.14E-07 | 1.76E-06 | 2.88E-06 | 3.67E-07 | 1.29E-08 | 1.41E-06 | 2.41E-06 | 9.87E-07 |
| Toluene | g | 1.15E-05 | 1.20E-05 | 1.42E-05 | 1.30E-05 | 1.63E-05 | 3.82E-05 | 7.58E-06 | 1.11E-05 | 1.81E-05 | 1.00E-05 | 7.20E-06 | 9.87E-06 | 1.67E-05 | 7.84E-06 |
| Trichloroethane | g | 6.87E-07 | 2.07E-07 | 1.04E-06 | 6.94E-07 | 3.85E-07 | 2.42E-07 | 4.26E-07 | 8.18E-07 | 1.34E-06 | 1.70E-07 | 6.03E-09 | 6.55E-07 | 1 .12E-06 | 4.59E-07 |
| Vanadium | g | 1.11E-05 | 3.81E-05 | 4.14E-06 | 4.68E-06 | 6.51E-05 | 2.94E-04 | 1.11E-05 | 2.05E-06 | 2.67E-06 | 4.44E-05 | 1.82E-06 | 5.99E-06 | 2.81E-06 | 2.67E-06 |
| Vinyl acetate | g | 2.61E-07 | 7.88E-08 | 3.96E-07 | 2.63E-07 | 1.46E-07 | 9.14E-08 | 1.62E-07 | 3.11E-07 | 5.09E-07 | 6.48E-08 | 2.29E-09 | 2.49E-07 | 4.26E-07 | 1.75E-07 |
| Xylene | g | 1.92E-06 | 1.52E-06 | 2.62E-06 | 2.44E-06 | 1.28E-06 | 1.23E-06 | 1.07E-06 | 2.15E-06 | 3.66E-06 | 7.56E-07 | 1.80E-06 | 1.67E-06 | 3.35E-06 | 1 .41E-06 |
| Zinc | g | 1.41E-05 | 4.85E-05 | 7.85E-06 | 1.66E-05 | 5.70E-05 | 2.00E-04 | 1.10E-05 | 3.51E-06 | 2.23E-06 | 4.17E-05 | 2.83E-05 | 7.70E-06 | 8.98E-06 | 1.1 4E-05 |
| Water emissions | | | | | | | | | | | | | | | |
| Acids ($H^+$) | g | 2.16E-08 | 1.06E-07 | 5.21E-09 | 6.62E-08 | 3.27E-08 | 6.55E-09 | 1.22E-08 | 4.17E-09 | 2.60E-09 | 3.42E-08 | 2.15E-07 | 1.34E-08 | 3.74E-08 | 2.93E- 08 |
| Aluminum ($Al^{3+}$) | g | 4.16E-07 | 8.91E-07 | 2.70E-07 | 4.08E-07 | 1.91E-06 | 5.87E-06 | 3.37E-07 | 2.39E-07 | 3.47E-07 | 1.08E-06 | 7.44E-08 | 2.67E-07 | 3.78E-07 | 1.11E- 07 |
| Ammonia ($NH^{4+}$, $NH_3$, as N) | g | 1.51E-04 | 1.67E-04 | 8.08E-05 | 1.20E-04 | 4.26E-04 | 1.12E-03 | 2.07E-04 | 1.88E-04 | 1.10E-04 | 2.97E-04 | 8.74E-06 | 1.54E-04 | 8.90E-05 | 6.09E-05 |
| AOX (adsorbable organic halogens) | g | 1.10E-12 | 2.34E-12 | 7.11E-13 | 1.08E-12 | 5.03E-12 | 1.55E-11 | 8.89E-13 | 6.31E-13 | 9.14E-13 | 2.85E-12 | 1.96E-13 | 7.04E-13 | 9.96E-13 | 2.94E-13 |

## Appendix B: Environmental burdens associated with generating 1 MJe electricity in the United States in 2000 [based on generation] (*cont'd*)

| | Unit | US average | ASCC | ECAR | ERCOT | FRCC | HICC | MAAC | MAIN | MAPP | NPCC | OFF-G | SERC | SPP | WSCC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aromatic Hydrocarbons (unspecified) | g | 2.57E-10 | 5.50E-10 | 1.67E-10 | 2.53E-10 | 1.18E-09 | 3.62E-09 | 2.08E-10 | 1.48E-10 | 2.15E-10 | 6.68E-10 | 4.60E-11 | 1.65E-10 | 2.34E-10 | 6.91E-11 |
| Barium ($Ba^{++}$) | g | 8.22E-10 | 1.77E-09 | 5.33E-10 | 8.08E-10 | 3.78E-09 | 1.16E-08 | 6.67E-10 | 4.73E-10 | 6.86E-10 | 2.14E-09 | 1.47E-10 | 5.29E-10 | 7.47E-10 | 2.21E-10 |
| BOD5 (biochemical oxygen demand) | g | 5.51E-04 | 1.18E-03 | 3.57E-04 | 5.42E-04 | 2.53E-03 | 7.76E-03 | 4.47E-04 | 3.17E-04 | 4.60E-04 | 1.43E-03 | 1.04E-04 | 3.54E-04 | 5.01E-04 | 1.49E-04 |
| Cadmium ($Cd^{++}$) | g | 8.56E-13 | 1.84E-12 | 5.55E-13 | 8.41E-13 | 3.93E-12 | 1.20E-11 | 6.94E-13 | 4.93E-13 | 7.15E-13 | 2.23E-12 | 1.53E-13 | 5.50E-13 | 7.79E-13 | 2.30E-13 |
| Chlorides ($Cl^-$) | g | 3.71E-02 | 9.80E-02 | 1.90E-02 | 2.41E-02 | 2.04E-01 | 6.82E-01 | 3.48E-02 | 1.36E-02 | 1.94E-02 | 1.22E-01 | 3.07E-03 | 2.23E-02 | 2.00E-02 | 9.07E-03 |
| Chromium (Cr III, Cr VI) | g | 5.77E-09 | 2.81E-08 | 1.40E-09 | 1.76E-08 | 8.81E-09 | 2.22E-09 | 3.27E-09 | 1.12E-09 | 7.16E-10 | 9.14E-09 | 5.71E-08 | 3.58E-09 | 9.96E-09 | 7.78E-09 |
| COD (Chemical Oxygen Demand) | g | 4.66E-03 | 9.98E-03 | 3.02E-03 | 4.58E-03 | 2.14E-02 | 6.57E-02 | 3.78E-03 | 2.68E-03 | 3.89E-03 | 1.21E-02 | 8.45E-04 | 2.99E-03 | 4.24E-03 | 1.25E-03 |
| Copper ($Cu^+$, $Cu^{++}$) | g | 1.71E-11 | 3.67E-11 | 1.11E-11 | 1.68E-11 | 7.87E-11 | 2.42E-10 | 1.39E-11 | 9.87E-12 | 1.43E-11 | 4.45E-11 | 3.07E-12 | 1.10E-11 | 1.56E-11 | 4.60E-12 |
| Cyanide ($CN^-$) | g | 1.20E-12 | 2.57E-12 | 7.78E-13 | 1.18E-12 | 5.50E-12 | 1.69E-11 | 9.69E-13 | 6.90E-13 | 1.00E-12 | 3.11E-12 | 2.15E-13 | 7.70E-13 | 1.09E-12 | 3.22E-13 |
| Dissolved matter (unspecified) | g | 6.65E-04 | 1.86E-05 | 1.94E-03 | 1.56E-04 | 4.85E-04 | 5.77E-05 | 1.21E-03 | 2.58E-04 | 2.39E-04 | 4.63E-04 | 1.91E-05 | 6.76E-04 | 1.17E-04 | 1.14E-04 |
| Fluorides ($F^-$) | g | 1.99E-04 | 1.33E-06 | 8.21E-05 | 1.21E-04 | 1.78E-04 | 3.49E-06 | 3.98E-04 | 3.95E-04 | 1.22E-04 | 2.55E-04 | 1.55E-06 | 2.88E-04 | 4.97E-05 | 1.12E-04 |
| Halogenated matter (organic) | g | 3.42E-13 | 7.34E-13 | 2.22E-13 | 3.37E-13 | 1.58E-12 | 4.83E-12 | 2.78E-13 | 1.97E-13 | 2.86E-13 | 8.91E-13 | 6.13E-14 | 2.20E-13 | 3.11E-13 | 9.23E-14 |
| Hydrocarbons (unspecified) | g | 2.39E-06 | 6.33E-06 | 1.22E-06 | 1.56E-06 | 1.31E-05 | 4.39E-05 | 2.25E-06 | 8.73E-07 | 1.25E-06 | 7.88E-06 | 2.25E-07 | 1.43E-06 | 1.29E-06 | 5.88E-07 |
| Iron ($Fe^{++}$, $Fe^{3+}$) | g | 3.87E-07 | 4.44E-09 | 1.59E-07 | 2.35E-07 | 3.48E-07 | 1.86E-08 | 7.70E-07 | 7.64E-07 | 2.36E-07 | 4.95E-07 | 3.27E-09 | 5.57E-07 | 9.69E-08 | 2.17E-07 |
| Lead ($Pb^{++}$, $Pb^{4+}$) | g | 3.42E-12 | 7.34E-12 | 2.22E-12 | 3.37E-12 | 1.58E-11 | 4.83E-11 | 2.78E-12 | 1.97E-12 | 2.86E-12 | 8.91E-12 | 6.13E-13 | 2.20E-12 | 3.11E-12 | 9.23E-13 |
| Mercury ($Hg^+$, $Hg^{++}$) | g | 3.94E-15 | 8.44E-15 | 2.55E-15 | 3.87E-15 | 1.81E-14 | 5.56E-14 | 3.20E-15 | 2.26E-15 | 3.29E-15 | 1.02E-14 | 7.05E-16 | 2.53E-15 | 3.59E-15 | 1.06E-15 |
| Metals (unspecified) | g | 5.72E-05 | 1.48E-04 | 3.01E-05 | 3.94E-05 | 3.08E- 04 | 1.02E-03 | 5.28E-05 | 2.23E-05 | 3.20E-05 | 1.84E-04 | 5.40E-06 | 3.46E-05 | 3.34E-05 | 1.41E-05 |
| Nickel ($Ni^{++}$, $Ni^{3+}$) | g | 1.71E-12 | 3.67E-12 | 1.11E-12 | 1.68E-12 | 7.87E-12 | 2.42E-11 | 1.39E-12 | 9.87E-13 | 1.43E-12 | 4.45E-12 | 3.07E-13 | 1.10E-12 | 1.56E-12 | 4.60E-13 |
| Nitrate ($NO^{3-}$) | g | 4.73E-05 | 6.45E-07 | 1.95E-05 | 2.89E-05 | 4.27E-05 | 3.00E-06 | 9.42E-05 | 9.35E-05 | 2.89E-05 | 6.07E-05 | 3.91E-07 | 6.82E-05 | 1.19E-05 | 2.65E-05 |
| Nitrogenous matter (unspecified, as N) | g | 4.63E-11 | 9.87E-11 | 3.00E-11 | 4.54E-11 | 2.13E-10 | 6.53E-10 | 3.75E-11 | 2.66E-11 | 3.86E-11 | 1.20E-10 | 8.27E-12 | 2.97E-11 | 4.20E-11 | 1.24E-11 |
| Oils (unspecified) | g | 4.03E-04 | 9.58E-04 | 2.35E-04 | 3.32E-04 | 2.02E-03 | 6.49E-03 | 3.51E-04 | 1.92E-04 | 2.77E-04 | 1.18E-03 | 5.40E-05 | 2.50E-04 | 2.96E-04 | 1.04E-04 |
| Organic matter (unspecified) | g | 5.73E-08 | 2.80E-07 | 1.38E-08 | 1.76E-07 | 8.64E-08 | 1.69E-08 | 3.24E-08 | 1.10E-08 | 6.86E-09 | 9.05E-08 | 5.71E-07 | 3.55E-08 | 9.87E-08 | 7.76E-08 |
| Phenol | g | 1.06E-05 | 2.27E-05 | 6.86E-06 | 1.04E- 05 | 4.86E-05 | 1.49E-04 | 8.58E-06 | 6.09E-06 | 8.84E-06 | 2.75E-05 | 1.91E-06 | 6.80E-06 | 9.60E-06 | 2.84E-06 |
| Phosphates ($PO_4^{3-}$, $HPO^{4-}$, $H_2PO^{4-}$, $H_3PO^4$, as P) | g | 1.85E-09 | 4.35E-09 | 1.14E-09 | 2.12E-09 | 8.05E-09 | 2.41E-08 | 1.47E-09 | 1.00E-09 | 1.44E-09 | 4.66E-09 | 1.75E-09 | 1.19E-09 | 1.80E-09 | 6.54E-10 |
| Polycyclic Aromatic Hydro-carbons (PAH, unspecified) | g | 4.11E-12 | 8.81E-12 | 2.66E-12 | 4.04E-12 | 1.89E-11 | 5.80E-11 | 3.33E-12 | 2.36E-12 | 3.43E-12 | 1.07E-11 | 7.35E-13 | 2.64E-12 | 3.74E-12 | 1.10E-12 |
| Salts (unspecified) | g | 4.73E-06 | 1.01E-05 | 3.07 E-06 | 4.65E-06 | 2.17E-05 | 6.68E-05 | 3.84E-06 | 2.73E-06 | 3.96E-06 | 1.23E-05 | 8.47E-07 | 3.04E-06 | 4.30E-06 | 1.28E-06 |
| Sodium ($Na^+$) | g | 4.79E-02 | 1.26E-01 | 2.44E-02 | 3.10E-02 | 2.62E-01 | 8.78E-01 | 4.49E-02 | 1.75E-02 | 2.51E-02 | 1.58E-01 | 3.96E-03 | 2.87E-02 | 2.58E-02 | 1.17E-02 |
| Sulfate ($SO^{4--}$) | g | 4.24E-05 | 7.96E-07 | 1.75E-05 | 2.59E-05 | 3.87E-05 | 4.13E-06 | 8.42E-05 | 8.36E-05 | 2.59E-05 | 5.46E-05 | 3.68E-07 | 6.09E-05 | 1.07E-05 | 2.38E-05 |
| Sulfide ($S^{--}$) | g | 1.20E-08 | 5.81E-08 | 2.87E-09 | 3.64E-08 | 1.80E-08 | 3.74E-09 | 6.74E-09 | 2.30E-09 | 1.44E-09 | 1.88E-08 | 1.19E-07 | 7.39E-09 | 2.06E-08 | 1.61E-08 |
| Suspended matter (unspecified) | g | 2.50E-03 | 5.36E-03 | 1.62E-03 | 2.46E-03 | 1.15E-02 | 3.53E-02 | 2.03E-03 | 1.44E-03 | 2.09E-03 | 6.50E-03 | 4.48E-04 | 1.61E-03 | 2.27E-03 | 6.72E-04 |
| TOC (total organic carbon) | g | 2.57E-09 | 5.50E-09 | 1.67E-09 | 2.53E-09 | 1.18E-08 | 3.62E-08 | 2.08E-09 | 1.48E-09 | 2.15E-09 | 6.68E-09 | 4.60E-10 | 1.65E-09 | 2.34E-09 | 6.91E-10 |
| Toluene | g | 3.77E-11 | 8.08E-11 | 2.44E-11 | 3.70E- 11 | 1.73E-10 | 5.31E-10 | 3.06E-11 | 2.17E-11 | 3.15E-11 | 9.78E-11 | 6.74E-12 | 2.42E-11 | 3.42E-11 | 1.01E-11 |
| Water: chemically polluted | liter | 5.51E-03 | 1.43E-02 | 2.87E-03 | 3.71E- 03 | 2.98E-02 | 9.94E-02 | 5.11E-03 | 2.10E-03 | 3.02E-03 | 1.79E-02 | 4.97E-04 | 3.32E-03 | 3.13E-03 | 1.36E-03 |
| Zinc ($Zn^{++}$) | g | 1.39E-09 | 6.70E-09 | 3.40E-10 | 4.20E-09 | 2.15E-09 | 6.55E-10 | 7.88E-10 | 2.73E-10 | 1.78E-10 | 2.21E-09 | 1.36E-08 | 8.58E-10 | 2.38E-09 | 1.86E-09 |
| **Wastes** | | | | | | | | | | | | | | | |
| Waste (hazardous) | kg | 1.79E-06 | 3.84E-06 | 1.16E-06 | 1.77E-06 | 8.24E-06 | 2.53E-05 | 1.46E-06 | 1.03E-06 | 1.49E-06 | 4.66E-06 | 3.20E-07 | 1.15E-06 | 1.63E-06 | 4.82E-07 |
| Waste (non hazardous) | kg | 1.43E-02 | 9.06E-03 | 2.45E-02 | 1.92E-02 | 1.22E-02 | 1.71E-02 | 1.16E-02 | 1.10E-02 | 1.88E-02 | 6.94E-03 | 6.31E-03 | 1.37E-02 | 1.62E-02 | 7.42E-03 |